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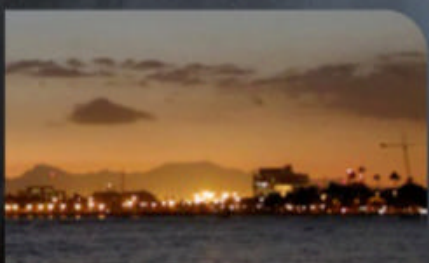
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VOL. 51, NO. 3



ON THE COVER

In 2017, a spectacular total eclipse washed over America. Next year another one will do the same.

BLAKE ESTES

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Everything you need to know about the universe this month: The Pillars of Creation get an update, Artemis 1 completes its mission, a new neutrino source is found, and more!

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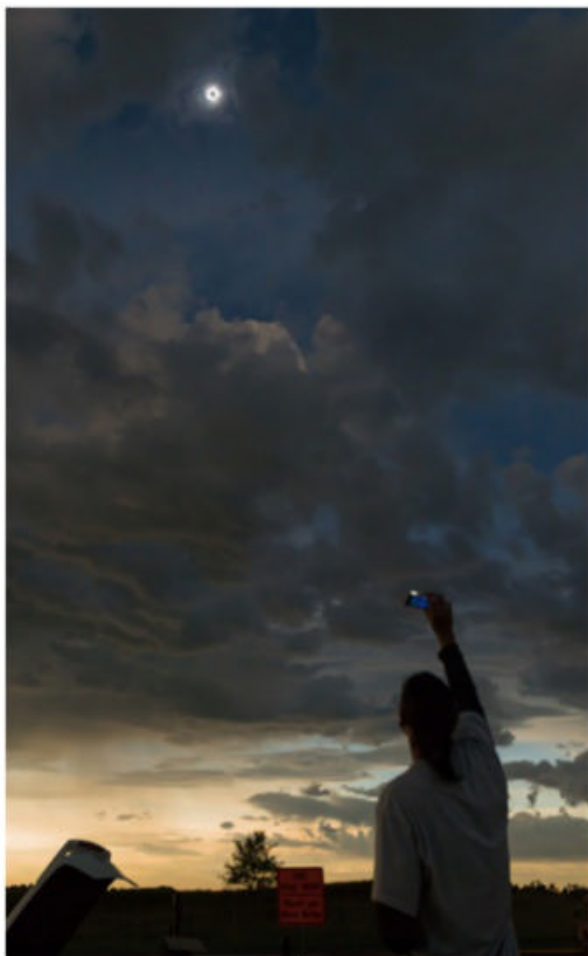


Dave's Universe

The inside scoop from the editor.

Astronomy (ISSN 0091-6358, USPS 531-350) is published monthly by Kalmbach Media Co., 21027 Crossroads Circle, P.O. Box 1612, Waukesha, WI 53187-1612. Periodicals postage paid at Waukesha, WI, and additional offices. POSTMASTER: Send address changes to *Astronomy*, PO Box 8520, Big Sandy, TX 75755. Canada Publication Mail Agreement #40010760.

Are you ready for 2024?



The American total eclipse in 2017 was widely viewed and cherished. In 2024, a total eclipse will again wash over the U.S.

JIM SCHAFF



On April 8 of next year, what promises to be the most viewed total eclipse in history will sweep across North America. Remember the amazing eclipse in 2017? More than 12 million Americans lived within the path of totality for that event. This time, the number who can simply walk outside and see the total eclipse (given clear skies, of course) soars to more than 31 million. More than half the U.S. population lives within 250 miles of the path of totality. It will be an astonishing, widely viewed celestial event.

If you don't know where you're going for the eclipse yet, it's high time to start figuring it out. The path moves through Mexico, Texas, Oklahoma, Arkansas, Missouri, Illinois, Indiana, Ohio, New York, Maine, and into Canada.

Michael E. Bakich's story "Plan for the 2024 total solar eclipse," on page 36, will give you a highly useful starting point for this adventure. Additionally, Michael has written "Simulate totality," page 48, which highlights

a website produced by veteran eclipse chaser Dan McGlaun that will help in many ways with your eclipse planning.

And please don't forget a mighty warmup act: this October's annular eclipse. On the 14th of that month, an eclipse that leaves a thin ring of sunlight around the Moon will carry across the American Southwest. The path moves from Oregon through Nevada, Utah, Arizona, New Mexico, and Texas.

This is merely the opening salvo. Expect to see continuing coverage in our pages and at Astronomy.com of these two big astronomical events. And try not to miss the 2024 total eclipse, especially. The next total eclipse to come in the U.S. won't occur until 2045.

Yours truly,

David J. Eicher
Editor



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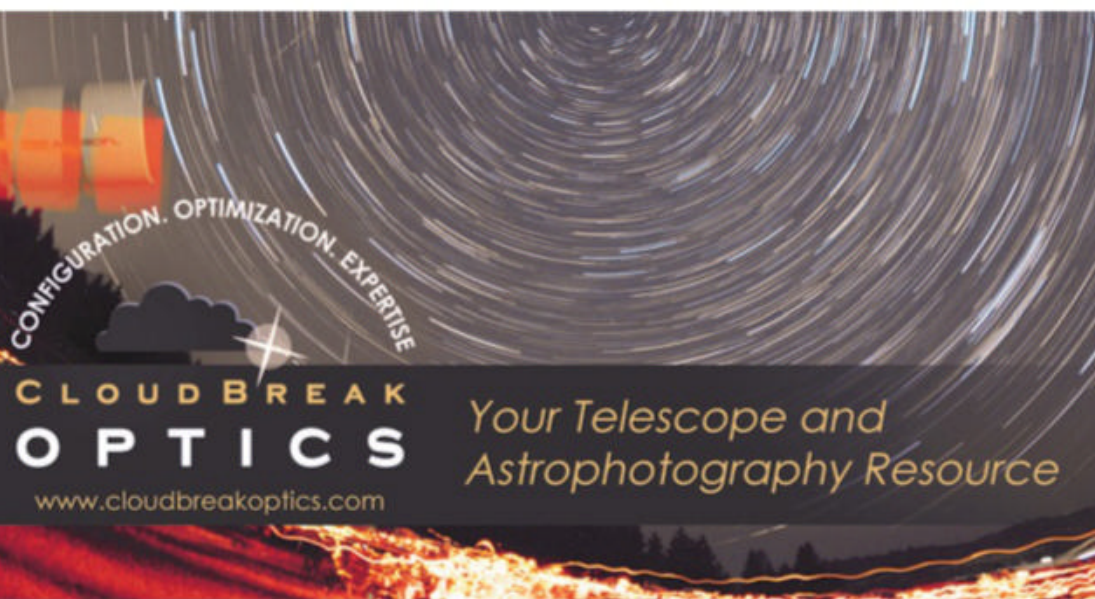
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Jupiter shines brightly to the upper left of the Moon, in this image dated Dec. 5, 2012.

JAMIE COOPER

 We welcome your comments at *Astronomy Letters*, P.O. Box 1612, Waukesha, WI 53187; or email to letters@astronomy.com. Please include your name, city, state, and country. Letters may be edited for space and clarity.

Following Jupiter

Although I have been gazing up at the night sky since I was quite young, my wife of 48 years never seemed as interested. However, after I shared details in Michael Bakich's October article, "Hail to the king," and explained Jupiter's location with respect to the Moon's location (based

on Martin Ratcliffe's and Alister Ling's summary in *Sky This Month*), she immediately picked out Jupiter on her own! And ever since that evening, she has been looking up to locate and observe Jupiter with very special excitement. — **Glenn Luzzi**, Mount Bethel, PA

Certain uncertainty

Just got my October copy of *Astronomy* with Stephen O'Meara's column on uncertainty. Wow, did it get me thinking about looking up into the sky and being uncertain about what I am seeing! Sometimes, sitting in my backyard, I will hear a plane flying at high altitude. I search the sky and I think I see this little silver object moving across the sky in front of me — or do I? And

then, as evening begins and I look up to the sky, there I think I see the first star of the evening. I look again and there's nothing — but I THINK I saw something, so I look more intently. I am sure I saw it ... or not sure at all. Thanks for Steve's uncertainty principle! It sure covers a lot of ground and makes me feel sure again. (I think.) — **Ron Hunt**, Maberly, Ontario

Errata

On page 46 of our November 2022 issue, we incorrectly spelled the first name of Darian Dixon. We apologize to Darian and the readers for this mistake.

Phil Harrington's November 2022 *Binocular Universe* column incorrectly stated that Matar is 45 million light-years distant. The star is in fact much closer, at 195 light-years. It is instead the spiral galaxy NGC 7331 that lies at the further distance. Additionally, the diagram accompanying the article incorrectly labeled the location of the Delphinus Minor asterism. The updated diagram is located on our website; use the QR code at the right to find it.



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SNAPSHOT

PILLARS OF OBSCURATION

JWST's infrared eye sees a famous scene in a new light.

For its latest trick, NASA's James Webb Space Telescope (JWST) performed a stellar disappearing act on the Pillars of Creation in the Eagle Nebula (M16), the star-forming region made famous by the Hubble Space Telescope. First, JWST captured the region with its Near-Infrared Camera (NIRCam), revealing myriad crimson stars forming within the Pillars (at right). Then, using its Mid-Infrared Instrument (MIRI), JWST made thousands of stars appear to vanish (at lower right). That's because stars typically don't emit much light at mid-infrared wavelengths. Rather, mid-infrared light unmasks dense regions of gas and dust. The red regions toward the top of this image are areas where dust clouds are relatively diffuse, while the blue-gray pillars consist of very dense dust. Using JWST's data, astronomers hope to figure out



exactly how much dust is in this region and what it is made of to better understand how these clouds incubate newborn stars. — JAKE PARKS



HOT BYTES



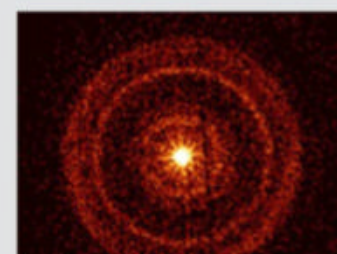
FINAL FLIGHT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) took its final science flight Sept. 29. SOFIA carried a 2.5-meter telescope aboard a modified Boeing 747SP and observed nearly the entire infrared range of light.



DEPOT DROP

NASA and the European Space Agency agreed Oct. 19 that the Perseverance Mars rover will cache samples at Three Forks in Jezero Crater as a backup for those the rover carries. The latter will be picked up in 2030 and returned to Earth in 2033.

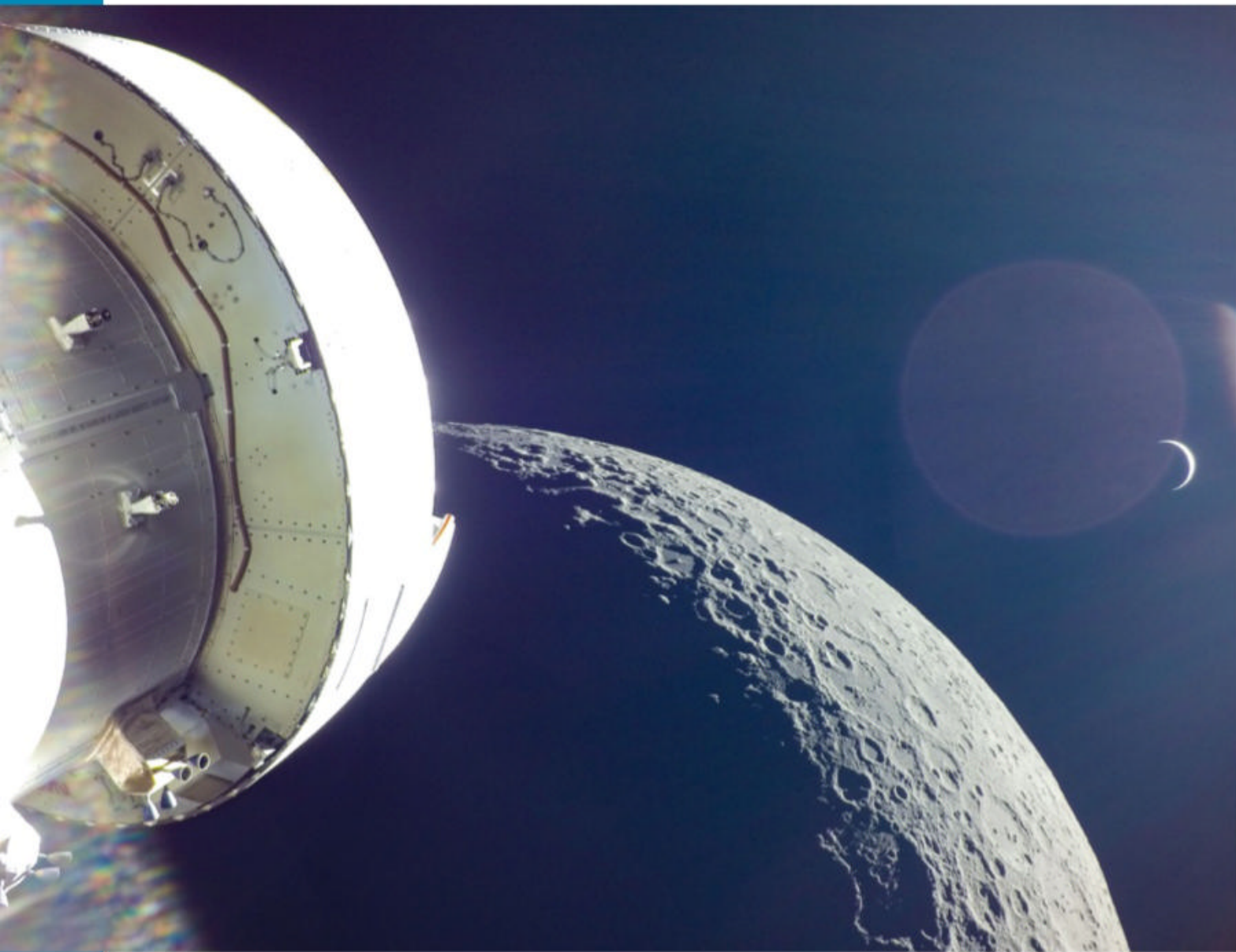


BRIGHT BURST

Gamma-ray burst 221009A arrived at Earth Oct. 9 after traveling some 2 billion light-years. Space- and ground-based telescopes captured the record-breaking explosion, which likely came from a star collapsing into a black hole.

ARTEMIS 1 COMPLETES HISTORIC MOON MISSION

The uncrewed flight paves the way for NASA to return humans to the Moon.



EARTHRISE 2.0. A crescent Earth rises behind the Moon in this image captured by the Orion spacecraft shortly after the powered flyby that sent it back to Earth. NASA

The rocket's second launch attempt Sept. 3 was scrubbed when a leak sprung while loading SLS's supercooled liquid hydrogen fuel — possibly caused by a mistaken command that overpressurized the system. SLS remained at the Kennedy Space Center's Launch Pad 39B while NASA attempted a fix.

NASA finally solved the issue ahead of a planned Sept. 27 launch window. Then came Hurricane Ian, which forced NASA to send the rocket back to the safety of the Vehicle Assembly Building.

In October, NASA began aiming for a Nov. 14 launch. The rocket was rolled back to the pad, only

for Hurricane Nicole to arrive shortly after. This time, though, the rocket stayed outside, and the launch window was pushed to the early morning hours of Nov. 16.

There were still hiccups: A small core-stage hydrogen leak forced a trio of technicians to go to the pad to tighten a valve on the mobile launcher. And a radar site that monitored the eastern launch range went dark due to a faulty ethernet switch that had to be replaced.

At 1:33 A.M. EST, NASA announced “no constraints” to launch and the countdown resumed. Six seconds before liftoff, the four core-stage liquid fuel engines started in rapid-fire succession.



NASA has finally taken its first small step toward sending humans back to the Moon.

Over the course of a 25-day flight, the uncrewed Artemis 1 mission launched aboard NASA's brand-new Space Launch System (SLS), looped around the Moon twice thanks to the European-built Service Module, and splashed down with the Orion capsule off Mexico's Baja California coast on Dec. 11 — the 50th anniversary of the Apollo 17 Moon landing.

In the runup to the launch, NASA officials had emphasized that the mission was a test flight. “We are stressing Orion beyond what it was

designed for,” said Bob Cabana, NASA's associate administrator, at a briefing. But Artemis 1 passed with flying colors, proving that the hardware meant to fly humans to the Moon is up to the task.

TRY, TRY AGAIN

It took some doing, though, just to get SLS off the ground.

After a series of tests throughout the summer and fall, the first launch attempt on Aug. 29 ended in a scrub. Among other glitches, one of the core stage's main engines failed to cool to the temperature required for launch. (Foul weather would have stalled the attempt anyway.)

As the countdown hit zero, SLS's solid rocket boosters ignited.

Artemis 1 lifted off into Florida's early-morning sky Nov. 16 at 1:47 A.M. EST as the Last Quarter Moon was rising over the Space Coast. Witnesses reported that they teared up, cheered, and felt the ground shake.

Two minutes after liftoff, the solid rocket boosters were jettisoned, looking like massive fireworks.

The core-stage main engine cutoff took place eight minutes into the flight at an altitude of about 100 miles (162 kilometers) before separating from the second stage, called the Interim Cryogenic Propulsion Stage (ICPS), which lifted the craft to orbit.

Just over two hours into the flight, the ICPS lit its engine again for trans-lunar injection, a nearly 18-minute burn that flung Orion from 17,500 to 22,600 mph (28,000 to 36,400 km/h) on toward the Moon. The ICPS was then jettisoned, though its role in the mission wasn't over: As it coasted to the Moon, the ICPS released a flotilla of 10 small satellites called cubesats, each with its own scientific objective.

A LUNAR TESTING GROUND

Artemis 1 began its lunar encounter by carrying out a flyby of the Moon Nov. 21, swooping as low as 81 miles (130 km) above the pockmarked landscape. The European Service Module's engine fired during the flyby, slinging the craft into a high, looping trajectory. Four days later, Orion reached its apolune of more than 57,000 miles above the Moon, and performed another burn to enter a distant retrograde orbit (DRO). During this phase of the flight, the capsule set a record for the farthest a human-rated craft has ever flown from Earth, some 268,563 miles (432,210 km).

After performing half an orbit around the lunar farside, Artemis 1 again fired its engine to exit DRO and drop toward the Moon for another powered flyby — this time, to fling it back home.

Orion raced toward Earth at around 25,000 mph (40,000 km/h), skipping once across the top of the atmosphere to achieve an optimal reentry trajectory. Three parachutes gracefully slowed the



RISING DESTINATION. The Moon shines over the Space Launch System and Orion spacecraft stacked at Launch Pad 39B at the Kennedy Space Center Nov. 14. NASA/BILL INGALLS

capsule to about 20 mph (32 km/h) for a splashdown at 9:40 A.M. PST, within sight of the USS *Portland*.

In a NASA statement, Artemis 1 Mission Manager Mike Sarafin said that Orion's deep-space performance had "exceeded our expectations," and the mission "demonstrated that Orion can withstand the extreme conditions of returning through Earth's atmosphere from lunar velocities."

NASA plans to launch Artemis 2 in 2024, carrying humans to lunar orbit for the first time in a half-century. And the crew of Artemis 3, which is scheduled for 2025, will alight on the lunar surface — including the first woman and first person of color to walk on the Moon.

Following the successful splashdown of Artemis 1, NASA Administrator Bill Nelson said: "It's historic because we are now going back into space, into deep space, with a new generation. We are adventurers, we are explorers, we always have a frontier; and that frontier is now to continue exploring the heavens." — CHRISTOPHER COKINOS

BLACK HOLE BURPS

In June 2021, astronomers spotted a black hole belching out material three years after it first tore apart and ingested a star. Normally, these eruptions last only a few months, so this delayed event opens new questions into how black holes digest stars.

ADIOS, ARECIBO

The National Science Foundation has decided not to rebuild the Arecibo radio telescope, whose main dish collapsed in 2020. Instead, the site will become an education and outreach center, the agency said Oct. 13.

EARLY WARNING

Massive stars may dim by up to 100 times in the year before they explode as a supernova, astronomers predict in a study published Oct. 13. This may give observers warning to train telescopes on likely targets.

GIVE IT A BOOST

NASA and SpaceX are brainstorming about how a Dragon spacecraft might boost the aging Hubble Space Telescope into a higher orbit, prolonging its working lifetime, the agency announced Sept. 29.

LAB GROWN

An alloy called tetrataenite, found in meteorites and formed over millions of years, is a possible alternative to rare Earth magnets required by many electric cars and other technologies. On Oct. 25, scientists reported a method to grow it in a lab in mere seconds.

SCHEDULE SHAKE-UPS

Psyche, a NASA mission to the metal-rich asteroid of the same name, missed its 2022 launch due to staff shortages. NASA announced Nov. 4 that it is diverting staff to it from the VERITAS Venus mission, delaying that spacecraft's launch from 2027 to 2031. — KOREY HAYNES

Donna Elbert's magnetic discovery

More than 60 years ago, a woman with no advanced training in mathematics created a theory for how planetary magnetic fields form. Her contribution was overlooked for decades but now, armed with modern techniques, astronomers are recognizing her powerful insight.

Donna Elbert worked with famed astrophysicist and Nobel laureate Subrahmanyan Chandrasekhar for more than 30 years at Yerkes Observatory in Wisconsin and the University of Chicago, starting in 1948. Throughout much of her career, Elbert was seen simply as a human computer — the term for people (mostly women) who cranked through numbers in the days before machines were capable of doing so. But in truth, she rapidly became an integral collaborator in his research.



POSTHUMOUS ACCLAIM. Donna Elbert, who died in 2019 at the age of 90, was a key collaborator of Subrahmanyan Chandrasekhar, but received little recognition during her lifetime for a crucial insight into planetary magnetic fields. DIANNE HOFNER SAPHIERE, SUSAN ELBERT STEELE, JOANNE ELBERT KANTNER

In the early 1950s, she and Chandrasekhar tackled the complex physics of planetary magnetic fields, which are generated when the charged particles of liquid metals inside planets rotate and churn. Elbert was the first to notice that if the forces from the rotation and the magnetic field are roughly equal in strength, convection in the liquid interior forms neat, large-scale circulation patterns instead of smaller, more turbulent ones. This is the sweet spot that lets a world host a strong global magnetic field like Earth's

— capable of shielding organisms from harmful radiation.

Though Elbert co-authored 18 other publications with Chandrasekhar, she was not credited as a co-author of the 1961 book in which this work appeared. Instead, Chandrasekhar acknowledged her contribution in a footnote — which most researchers overlooked.

Recently, Susanne Horn of Coventry University in the U.K. and Jonathan Aurnou of the University of California, Los Angeles, returned to Chandrasekhar and Elbert's work, having noticed the footnote. In her honor, they named the scenario the Elbert range and built upon her original analysis with modern computing power. The results were published Aug. 10 in *Proceedings of the Royal Society A*.

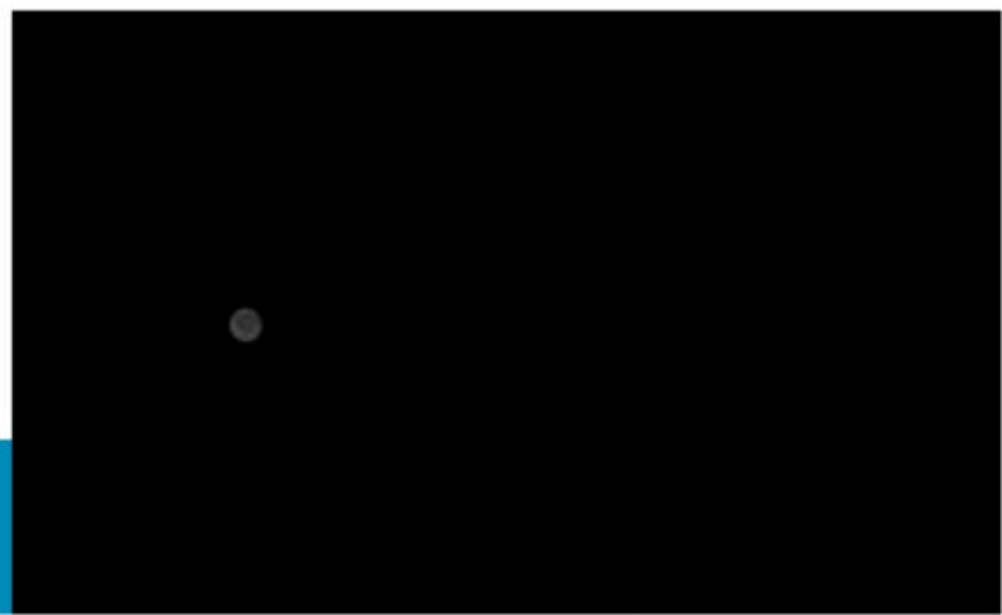
The work may help scientists better understand Earth's own magnetic field, as well as potentially point to exoplanets that could likewise sustain global magnetic fields strong enough to protect life. — K.H.



NASA, ESA, CSA, STSCI, JPL-CALTECH

BINARY SIGNATURE

The rings in this image are not an artifact — though at first glance, puzzled scientists thought they were. Rather, they are made of dust surrounding the binary system WR 140, as captured by NASA's James Webb Space Telescope and its Mid-Infrared Instrument. The system features a Wolf-Rayet (WR) star, which is so hot and massive it is rapidly blowing its outer layers of gas into space. The explanation for the regular spacing of these dust rings is reported in a pair of papers published Oct. 12 in *Nature* and *Nature Astronomy*: Every eight years, when the WR star and its companion star approach each other in their elliptical orbits, their winds collide, and the enhanced pressure and radiation transforms some of that gas into dust. Although the features appear ringlike, in 3D space they are more like nested shells. — MARK ZASTROW





NEUTRINOS STREAM FROM BLACK HOLE

WHEN COSMIC RAYS run into dust and radiation, they produce particles that eventually decay into gamma rays and neutrinos. These messengers flood the cosmos from all directions. But while gamma rays can be readily detected, neutrinos — which rarely interact with matter — are much harder. Until recently, astronomers could point confidently to just one galaxy known to produce them.

Now, there is strong evidence for a second: the bright spiral M77 (NGC 1068) in Cetus, around 45 million light-years away. In a paper published Nov. 3 in *Science*, researchers report fresh observations from the IceCube neutrino observatory at the South Pole, plus improved analysis techniques that draw on machine learning. Combined, the results indicate M77 is the origin of 79 neutrinos that IceCube detected

NATURAL RESOURCE. IceCube uses 0.24 cubic mile (1 cubic km) of ice with edges 0.6 mile (1 km) long, laced with optical sensors to detect when a neutrino hits the ice. This produces secondary particles that emit light as they speed through the ice. MARTIN WOLF, ICECUBE/NSF

over the past decade. The IceCube team had tentatively reported M77 as a possible neutrino source in 2020, but the evidence wasn't strong enough to claim a clear detection; the new analysis changes that.

The findings offer a glimpse into the super-massive black hole at M77's heart, suggesting its magnetic field acts as a powerful particle accelerator that produces cosmic rays — which, in turn, create neutrinos and gamma rays.

But while M77 appears to be producing neutrinos, it is not particularly bright in gamma rays. It also lacks the blazing jets of near-light-speed material that emanate from the only other known galaxy to produce neutrinos, the blazar TXS 0506+056.

Astronomers suspect that M77's core may be one whose gamma rays are "hidden," perhaps obscured by dust. Such galaxies and the cosmic rays they produce may be crucial in accounting for the number of neutrinos observed in the sky. —M.Z.

1,560

The approximate distance, in light-years, of Gaia BH1, a system that may host a black hole — the nearest to Earth yet known. It is three times closer than the previous closest-known black hole to our planet.

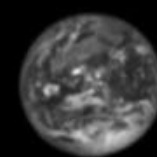


26 percent

The decline in investment in space startups year over year in Q3 2022, down from a record high in 2021, according to *Space Investment Quarterly*.

Lucy's humbling snapshot

NASA's Lucy spacecraft captured this view of Earth, the Moon, and the vast desert between them from a distance of 890,000 miles (1.4 million kilometers) Oct. 13. The spacecraft was approaching Earth to execute its first of three planned gravity assists, which will boost it to the speeds needed to reach Jupiter's orbit. The Lucy mission is designed to explore one main-belt asteroid and several of Jupiter's Trojan asteroids, which form two camps that lead and follow the gas giant in its orbit around the Sun. —J.P.



The cubic centimeter

Measuring cosmic volume is surprisingly down to Earth.



We can visualize the standard unit of volume throughout the universe with the help of a single earthly object: the sugar cube. TATYANA NYSHKO/DREAMSTIME



We all survey the vastness of space with a certain amount of wonder and awe. Exploring and understanding the cosmos requires units to express its size — including volume. But because of that vastness, we often revert to nonstandard metaphors to help convey it.

To express the volume of something big, like the Sun for example, writers commonly say that a million planet Earths would fit inside it. Tiny objects demand similarly creative analogies. The universe contains mostly hydrogen atoms, whose mass is concentrated in the nucleus, usually as a single proton. That proton is 1,836 times heavier than the electron buzzing around it. But a true picture requires us to also visualize its structure, which is mostly empty space. We'd succeed by representing that proton as a raisin in the middle of a football field and letting the electron be a barely visible fairyfly in the upper grandstand.

But analogies only go so far. To make detailed comparisons, we really need a single multipurpose volume unit. Science has chosen the cubic centimeter (cm^3). Happily, there's an earthly object exactly that size: the sugar cube.

In the U.S. in the 1960s, the displacement of motorcycle and car engines — which had previously been

expressed in cubic inches — increasingly began to be cited in cubic centimeters, abbreviated as cc. Soon most people understood that motorbikes like the Honda 50 had 50cc engines that were wimpy but cheap and maneuverable. And today, most Americans know a 600cc motorcycle is a substantial cruising machine because we're now accustomed to cubic centimeters. Making comprehension even easier, 1 cubic centimeter of water weighs exactly 1 gram (the same weight as a U.S. dollar bill), making the density of water 1 g/cm^3 .

This makes it easy-peasy to put into perspective Earth's overall density of 5.5 g/cm^3 , the highest of any planet in the solar system. And knowing Saturn's density is 0.7 g/cm^3 suggests it's composed of light elements like helium and explains why it would float on water.

In fact, all sorts of revelations spring forth when we use cubic centimeters. We've already seen that each atom is mostly empty space, so it makes sense that there is very little actual material in our lives — or our bodies. If we took the entire human race of some 8 billion people and removed all the empty spaces in and between our atoms, our matter alone — basically everyone's combined atomic nuclei — would fit inside a single sugar cube. That's right, our entire species amounts to 1 cubic centimeter of solid material after you've removed the empty spaces. *Plop!* Drop us into a cup of tea.

But we're here to stretch our minds with mostly unknown insights, and you might have heard that one. So, how's this second fact: The brightness of the cosmos essentially boils down to how many photons it contains. A photon-less universe would be pitch black. Well, the cosmos has a billion photons for each of its protons. But

what does that mean, given its vast empty space? A more helpful answer is that, on average, our cosmos has 413 photons per cubic centimeter! That's why we see pretty things through our telescopes.

Finally, since we love superlatives, what's the highest density we can express in cubic centimeters? Not a black hole's density, since the singularity itself may reach infinite density, though many physicists protest that infinite density is a concept devoid of any

real-world physical meaning. But neutron stars are different. These, like the Crab Pulsar, are objects with stable densities. So, what density is a neutron star? Answer: 100 trillion g/cm^3 . That's the equivalent of a single sugar cube weighing a hundred million tons — a sugar cube equaling the mass of 640 cruise ships.

Still think this isn't a strange universe? 🌌

All sorts of revelations spring forth when we use cubic centimeters.



BY BOB BERMAN
Bob's recent book, *Earth-Shattering* (Little, Brown and Company, 2019), explores the greatest cataclysms that have shaken the universe.



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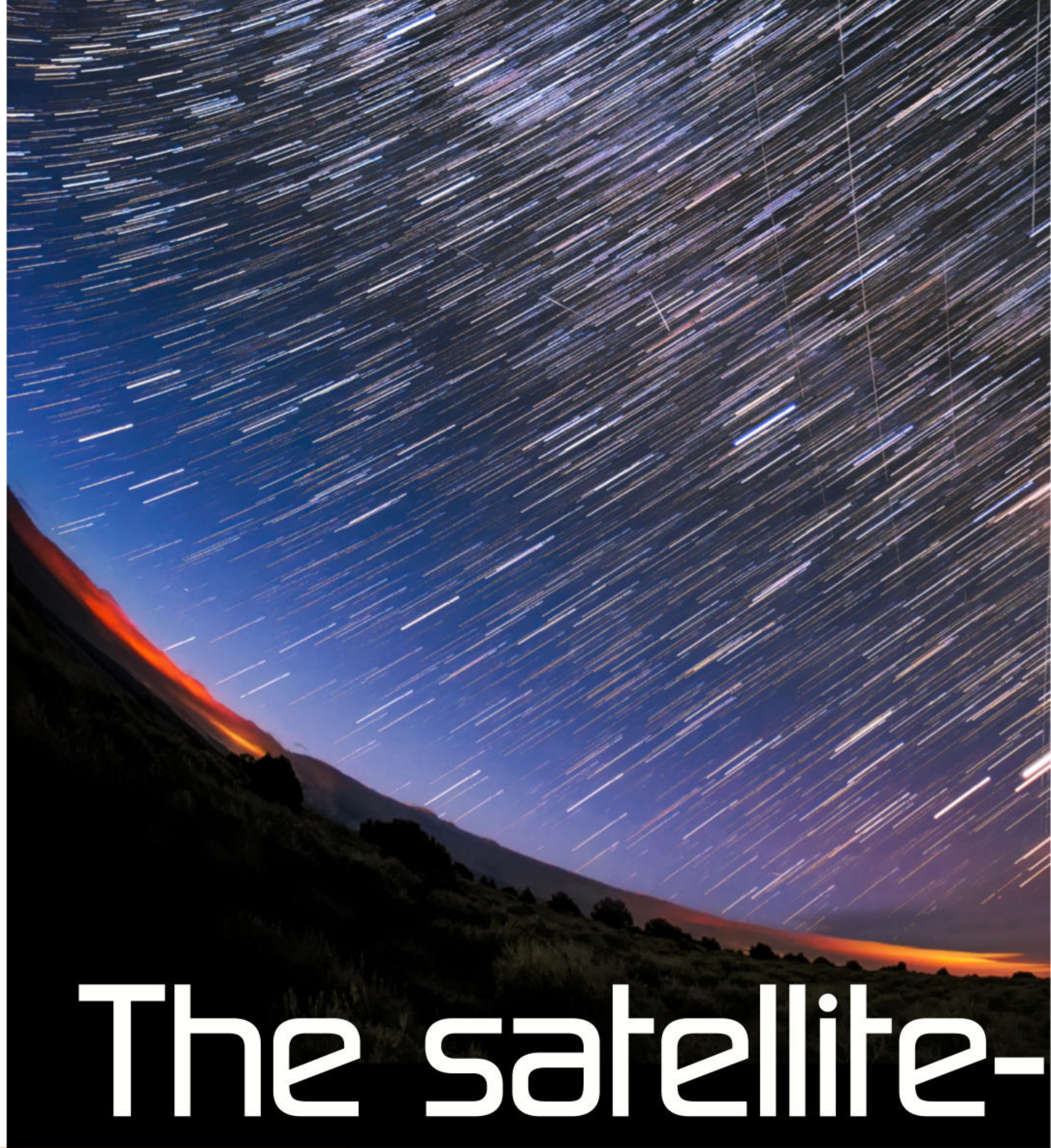
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The satellite-

The rise of
megaconstellations is
changing the night sky
forever and forcing
astronomers to adapt.

**BY MEREDITH RAWLS
AND JEFFREY HALL**



ON THE NIGHT OF MAY 25, 2019, astronomy educator Victoria Girgis was conducting a public stargazing session at Lowell Observatory in Flagstaff, Arizona. A telescope and camera were trained on NGC 5353/4, a magnitude 11 galaxy group in Canes Venatici, when suddenly the image was photobombed by an extremely bright train of satellites streaking through the field of view.

Around the world, astronomers were seeing the same thing — and quickly realized the culprit: Just two days earlier, SpaceX had launched a Falcon 9 rocket carrying the first 60 satellites of the company's new Starlink satellite system, designed to provide broadband internet access around the world.



streaked sky

 Starlink satellites, photographed soon after launch, pass overhead near Carson National Forest, New Mexico. M. LEWINSKY/
CREATIVE COMMONS ATTRIBUTION 2.0

The astronomy community and SpaceX were both caught by surprise at just how bright these new satellites were. Prior to 2019, there were only about 200 satellites visible to the unaided eye. But with a visual magnitude of 3 or brighter, Starlink satellites outshone all but 170 stars.

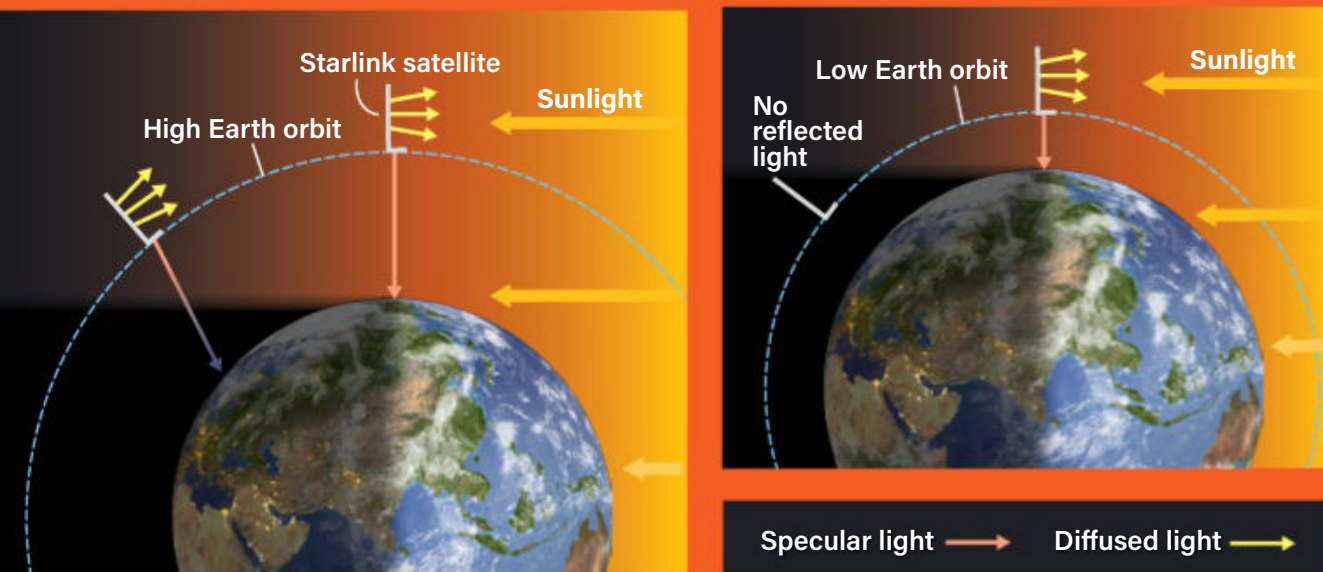
It was a watershed moment in humanity's use of space. Today, we live in a world where low Earth orbit (LEO) is no longer predominantly the domain of major national agencies like NASA. Private companies can launch massive fleets of satellites, limited only by their vision and resources. SpaceX plans for its first generation of Starlink to have about 4,400 satellites, over half of which have already been launched. In December

Starlink won approval to launch 7,500 Gen 2 satellites, and plans to expand to 30,000 satellites, with routine controlled deorbits and new launches to replace old hardware.

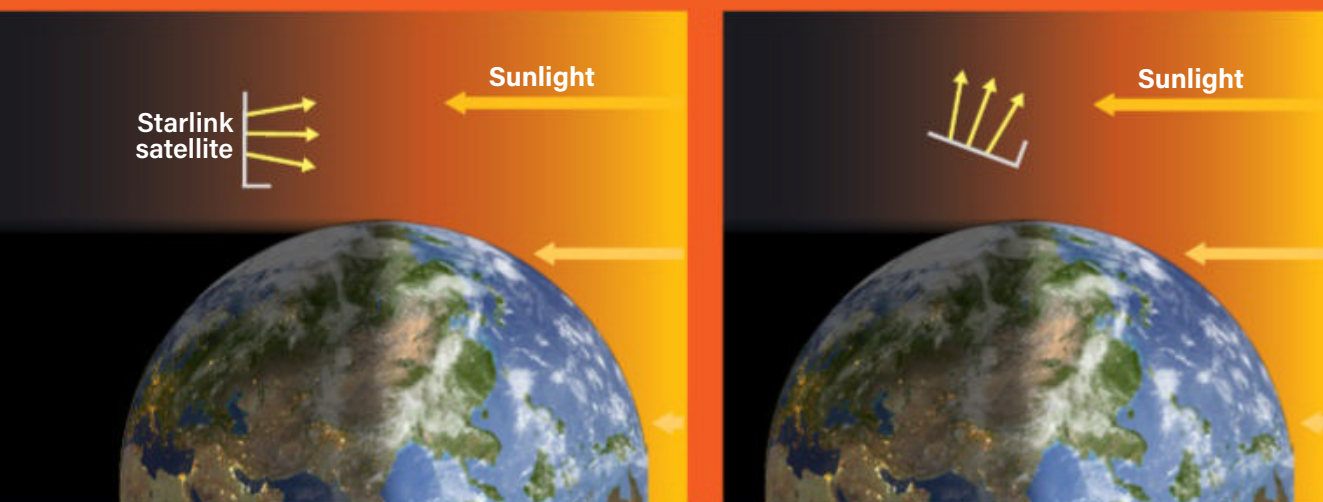
And Starlink is but a single constellation. Other operators like Amazon's Project Kuiper (planning to begin launches of prototypes in early 2023 and eventually have a constellation of 3,236 satellites) and OneWeb (with 600 satellites set to be operational by early 2023) have their own fleets on the way. Plus, dozens of national and private agencies around the world have expressed interest in their own constellations.

HOW TO DIM A SATELLITE

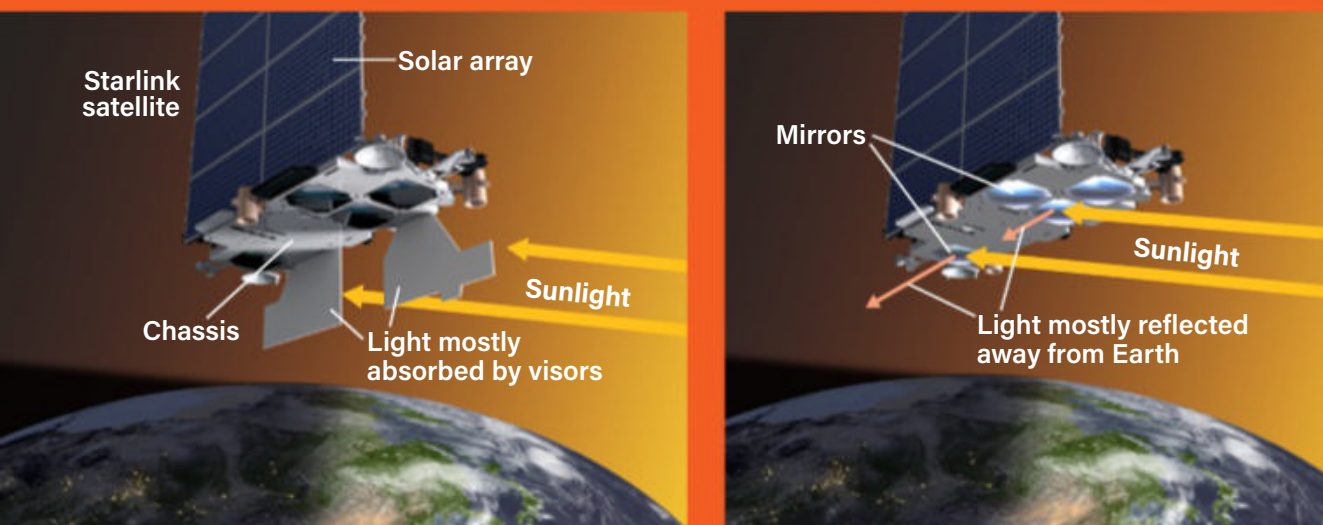
THERE ARE NUMEROUS STRATEGIES that can potentially reduce the impact of satellite trails on astronomy. However, many of them come with trade-offs.



Orbiting at a higher altitude will reduce a satellite's apparent brightness to ground observers. But it will also be lit by the Sun for more of its orbit, making it visible across more of the sky and during more of the night.



Satellites can be oriented so reflective surfaces like solar panels reflect light away from Earth, but this can reduce the amount of sunlight they gather and the power they generate. SpaceX says it will design its next generation of Starlink satellites to cope with less power.



To limit the amount of light reflecting off the bottom of the satellite body, SpaceX tried installing sun visors. However, the company said that these interfered with the laser communication links the satellites need to expand their coverage to remote regions. The visors also increased drag, removing the satellites from orbit more quickly. As an alternative, the company is developing mirror films that can scatter and direct light away from Earth. Using darker materials and black paint can also limit reflectivity by absorbing light. However, it can also raise temperatures and reduce the performance of components like solar arrays.

The situation is clear: We are racing toward a cloud of bright LEO satellites numbering in the hundreds of thousands that will fundamentally change the night sky. And we are only just beginning to understand the ramifications for astronomy — and humanity — of this massive sea change in our use of orbital space.

The life cycle of a satellite

It takes LEO satellites about 90 minutes to orbit Earth, zipping along at around 17,500 mph (28,200 km/h). This makes bright ones easy to spot, reflecting sunlight as they steadily transit across the sky, often to the delight and curiosity of novice observers. But after the novelty has worn off — and, say, four more have been spotted inside 15 minutes — the implications are a bit staggering.

Satellites bound for an LEO constellation appear brightest and most clumped together in the few days or weeks after launch. Thus, it's during this time that they have the greatest visual impact. Eventually, using thrusters, the satellites make their way to a higher orbit, where they will spend most of their operational life. From there, they are fainter, and telescope cameras are more likely to see only one or two streaks at a time. The width and brightness of these streaks can vary with many factors, including the size of the telescope, the satellite's altitude, the wavelength of light being observed, and the shape and material of the satellite itself.

Typical LEO satellites are designed for a lifetime of up to five years, and U.S. operators are required by the Federal Communications Commission to have a plan to deorbit their satellites to avoid contributing to the growing amount of space junk. Thus, their destiny is to be a human-made meteor — burning up in Earth's atmosphere as a bright, short-lived fireball. Of course, most satellite operators want to maintain (or grow) their constellation, so a satellite's demise does not change the overall situation; one or more will take its place.

Scientific impacts

The reach of ground-based light pollution is limited. Gloriously dark starscapes do still exist, draped across remote mountaintops and national parks. But this will not be true in a future where

light pollution also comes from above, blanketing the sky with large and bright LEO satellite constellations.

How much these satellites will ultimately affect our ability to do cutting-edge science from ground-based astronomical observatories is not entirely clear yet. This is still a new and rapidly evolving problem. So far, research shows that satellite constellations have varying impacts on different kinds of science. Those impacts depend on how bright and wide each individual satellite streak is and how “glinty” it behaves — when surfaces of the spacecraft directly reflect sunlight, like the glare off a shiny car.

One study from researchers at the Zwicky Transient Facility published in *The Astrophysical Journals Letters* in January 2022 found that satellite streaks had not significantly impacted their work — yet. But this and other studies predict a startling stymieing of discoveries in the next few years.

It’s clear that any investigation that relies on detecting objects close to twilight will be severely hindered, as more satellites are illuminated by the Sun at that time. For example, discovering near-Earth asteroids — including potential threats that could impact Earth — will be significantly more challenging.

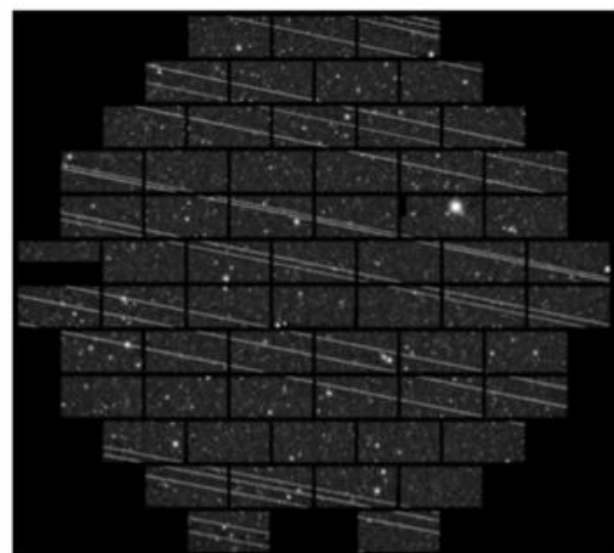
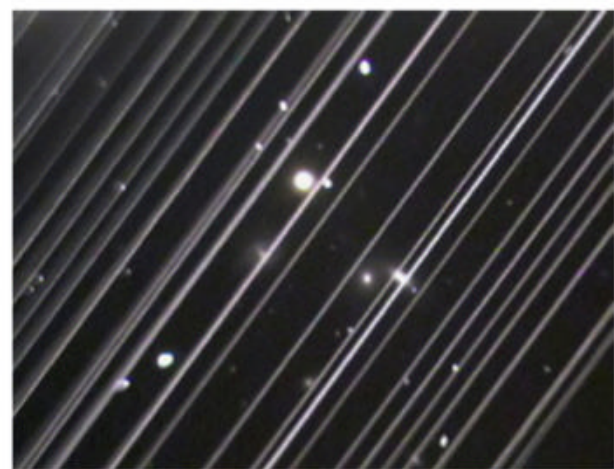
In addition, the ever-present disruption of satellite streaks, even one or two per image, means that it will be a lot harder to obtain a smooth background sky to calibrate observations. This can affect measurements of key phenomena like gravitational lensing — the bending



 A train of Starlink satellites soars over the Indian Ocean and a soft auroral glow in this image taken from the International Space Station. NASA

 The first full batch of 60 Starlink test satellites launched to low Earth orbit May 24, 2019. On the night of May 25, more than 25 of the satellites left trails across this image. VICTORIA GIRGIS/LOWELL OBSERVATORY

 A slew of at least 19 Starlink satellites cross the field of view of the Dark Energy Camera on the 4-meter Victor M. Blanco telescope in Chile Nov. 13, 2019. CTIO/NOIRLAB/NSF/AURA/DECAM DELVE SURVEY



Any study relying on spectroscopy — breaking up light into its constituent wavelengths to investigate an object’s motion, elemental composition, and more — will be susceptible to surprise satellite photobombs. And any survey that combs through images searching for changes — distant explosions or stellar flares, perhaps — is likely to be regularly fooled by glints.

Finally, as the active satellite population grows, so will the amount of space junk, from sources like collisions, rocket explosions, and even micrometeroids sandblasting away bits of solar panels. This diffuse cloud of debris will reflect and scatter light, which studies suggest will brighten the overall sky background.

All these impacts are generally greatest for wide-field observatories with large mirrors and sensitive cameras, like the Vera C. Rubin Observatory, which is under construction in Chile and due to begin a 10-year survey of the southern sky in 2024.

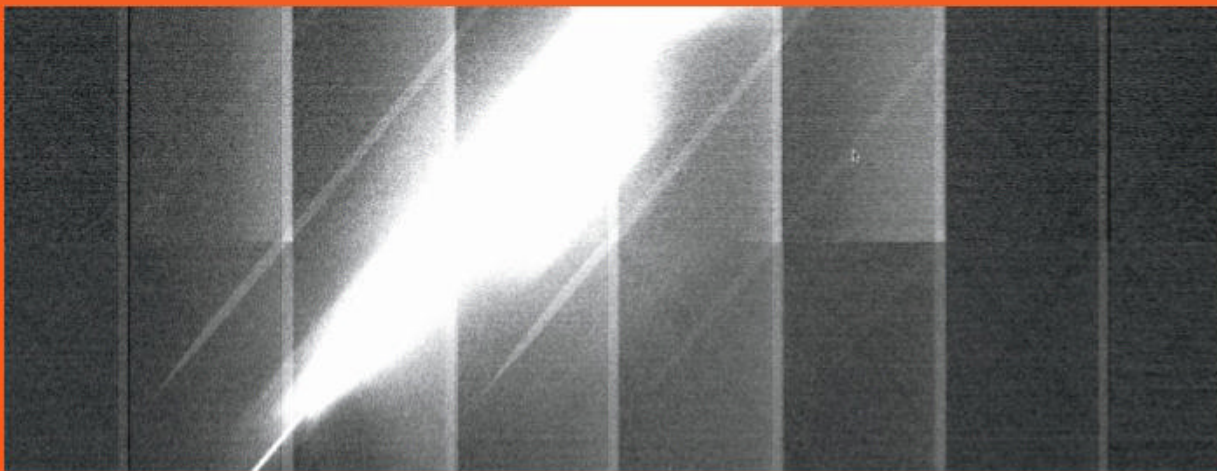
But radio astronomers are also

extremely concerned, as all these satellites transmit information down to Earth, which can interfere with astronomical observations. Regulatory agencies have reserved some slivers of radio frequencies for science, but the spectrum is already extremely crowded and some radio-frequency interference (RFI) can bleed into protected bands.

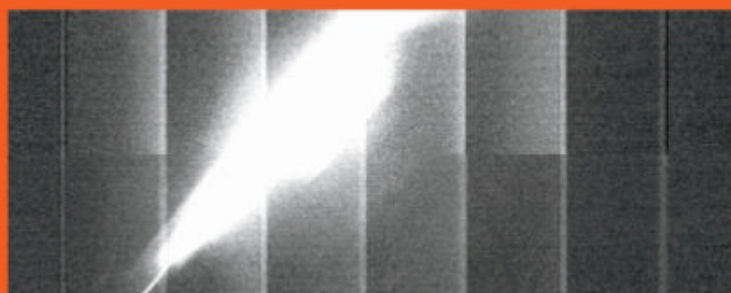
Until recently, much RFI came from satellites in the geosynchronous and geostationary belt that appear stationary, or from a handful of satellites in medium

**We are racing toward
a cloud of bright LEO
satellites that
will fundamentally
change the night sky.**

of light by massive objects, like galaxy clusters. So, if you were hoping to learn more about the fate of our universe by studying how this effect very subtly alters the distribution of galaxies we see in the sky, you may be in for a rough ride.



▶▶ Satellite streaks can affect the readout of other pixels. The crisscrossing streaks in the above image — produced in a lab test by researchers at the Rubin Observatory — are examples of this phenomenon, called crosstalk. If satellites are dimmer than 7th magnitude, crosstalk can be eliminated by software (right). ANDREW BRADSHAW/SLAC/VERA C. RUBIN OBSERVATORY



Earth orbit that trace predictable paths across the sky. Thousands of satellites in LEO screaming all over the place, day and night, are a different story altogether.

Broader implications

Of course, science is not the sky's only purpose. It is also important to remember the bigger picture. The proliferation of LEO satellites makes it harder for the public to view and enjoy the natural night sky, increases the likelihood of collisions that may impact space operations, and threatens to erase the knowledge and traditions of Indigenous peoples around the world that are based on the night sky.

It also has environmental repercussions. Each rocket launch contributes emissions to the atmosphere and the fiery cremation of reentering satellites deposits microscopic debris. Of particular concern is aluminum, which is much more common in spacecraft than in natural micrometeoroids. Burning these particles creates aluminum oxides, which scatter light and could even alter Earth's overall albedo.

The debris that does make it through to the lower atmosphere and to Earth's surface may also disrupt marine ecosystems and put aircraft and people on the

ground at risk. One recent study estimates that with a population of 16,000 satellites in LEO, fragments from reentering satellites would kill a person roughly every four years on average.

Satellite constellations may also disrupt animal life in ways we don't yet understand. For instance, many species use the stars and Milky Way to orient themselves, including birds that migrate at night, and it's possible that low-flying satellites that appear as new "stars" in the sky may confuse them.



▶ Starlink satellites have an L-shaped profile, with a flat chassis and a tall solar panel. Both can reflect sunlight toward the ground, depending on the craft's orientation. ALEKSANDR KUKHARSKIY/SHUTTERSTOCK

In an April 2022 perspective in *Nature Astronomy*, a group of astronomers (including one of the authors of this article) argued that LEO should be considered as an ecosystem that needs care and regulation, just like the oceans and atmosphere.

The American Astronomical Society (AAS) has also convened two workshops, dubbed SATCON1 and SATCON2, on satellite constellations. One of the recommendations to emerge from those workshops — held in 2020 and 2021 — is to slow or stop the pace of launches until we can better understand all the issues and meaningfully develop solutions. However, there do not appear to be any plans at the moment among satellite operators to slow launches or establish a more consensus-based approach for utilizing orbital space.

Managing the impacts

Immediately after the first Starlink satellites launched in 2019, the astronomical community reached out to several satellite operators — including SpaceX, Amazon Kuiper, and OneWeb — to try to work together to reduce the impact on astronomy. So far, most of the design and engineering work to achieve this goal has been with SpaceX, as they are the first with a large satellite fleet in operation.

SpaceX has experimented with numerous strategies to reduce the amount of light Starlink reflects back to Earth, such as painting various components of satellites black. The company also tried added visor shades to block sunlight from reaching reflective surfaces, and reoriented satellites so that less of the reflective surface is pointed toward Earth. However, SpaceX found that the visors interfered with the satellites' communications and also added a significant amount of drag, requiring satellites to burn more fuel to stay aloft. In place of the visors, SpaceX has added a special coating designed to reflect light strongly in one direction, away from Earth.

These early experiments demonstrated that Starlink satellites in their operational orbits could be darkened from visual magnitude 5.0 to about 6.0 or 6.5, close to the limit of the unaided eye. However, they appear brighter in redder wavelengths, which could still impact infrared astronomy.



 Starlink satellites await deployment after being launched to low Earth orbit. SPACEX REJECTS

These efforts reveal the complex nature of the sudden transformation in humanity's use of LEO. On the one hand, we must be clear: Even the most heroic efforts by satellite operators cannot eliminate a substantial impact on astronomy. The SATCON1 workshop concluded that a visual magnitude of 7.0 for satellites at altitudes of 370 miles (600 kilometers) or lower was needed to mitigate the most severe impacts on images from facilities like the Rubin Observatory. This includes the removal of crosstalk trails — secondary image artifacts caused when a bright object affects the readout of other pixels. But this still leaves the main bright streak to be dealt with — a complex problem to correct.

The use of lower altitudes — which can reduce how long satellites are visible overnight — is also a compromise, as it is less effective for telescopes at higher latitudes. And the lower the constellation, the more satellites are needed to achieve global coverage. In the end, there is no way to make LEO satellites invisible even to

the smallest amateur telescopes, let alone 8-meter behemoths.

On the other hand, we acknowledge the substantial time, effort, and money SpaceX has invested in redesigning its satellites. The interaction between astronomers and satellite operators has been both constructive and cordial.

The good news is that, in principle, it appears most Starlink satellites can be made invisible to the human eye once they are in their operational orbits. And although the internet and communication services offered by companies like SpaceX are not humanitarian missions,

they have support from many geographically isolated constituencies and the potential to benefit those afflicted by natural disasters and other crises.

Charting the future of space

The transformation of human access to space is not a black-and-white issue. Astronomy is just one of many communities that can lay claim to a legitimate use of

space. Comprehensive solutions to managing space in this new era will need the creativity and cooperation of many more parties, such as regulatory bodies and environmental groups. And it will require elevating the voices of those who are traditionally ignored and marginalized each time a new frontier is repurposed.

This is a challenge, but it can also be an opportunity. The world is sorely in need of such collaborative efforts, and perhaps the frontier of space can serve as a canvas on which humanity can seek visionary solutions.

If you'd like to help, the authors welcome you to apply to join the new International Astronomical Union Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (<https://cps.iau.org>).

We also encourage you to seek out a dark site to marvel at the night sky, because it may soon not look the same. 🌌

READ MORE!

You can access the executive summaries and technical reports of the SATCON1 and SATCON2 workshops online. You may also be interested in the reports of the international Dark and Quiet Skies I and II conferences, which include sections on satellite constellations as well as other dark-sky and RFI issues.



Meredith Rawls is an astronomer at the University of Washington and the Vera C. Rubin Observatory. **Jeffrey Hall** is executive director of Lowell Observatory. Both are members of the AAS Committee on Light Pollution, Radio Interference, and Space Debris.

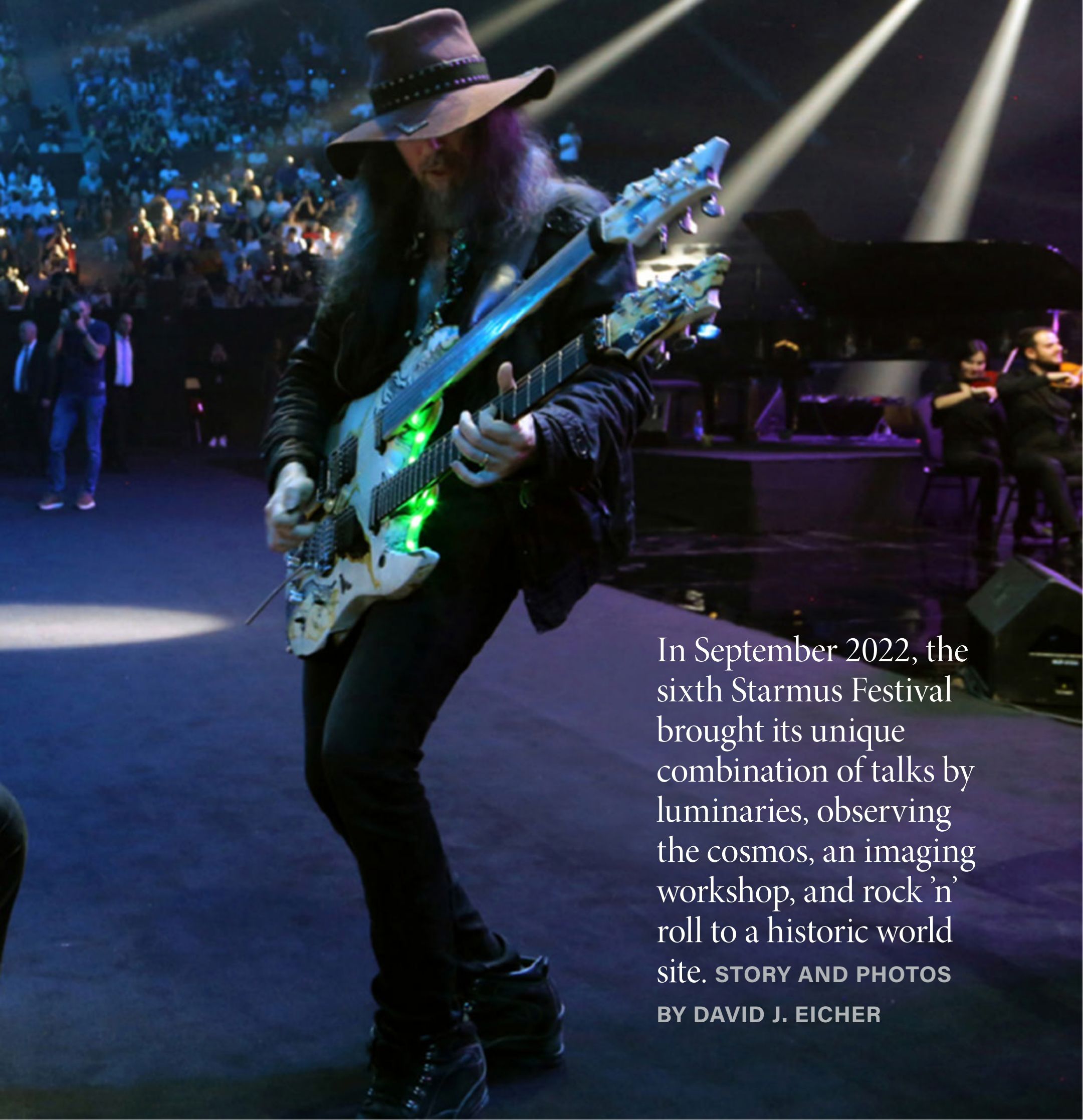
STARMUS ROC



Ace guitarist
Bumblefoot Thal of
the Sons of Apollo
scorches a solo in front
of an admiring Brian
May during a Starmus
concert night.

DAVID J. EICHER, MARS (UPPER RIGHT):
MARTIN HOLVERDA/DREAMSTIME

KS ARMENIA



In September 2022, the sixth Starmus Festival brought its unique combination of talks by luminaries, observing the cosmos, an imaging workshop, and rock 'n' roll to a historic world site. **STORY AND PHOTOS**

BY DAVID J. EICHER

A

dozen years ago, two inventive minds got together and launched the Starmus Festival, an international celebration of science and music. Its creators, astronomer Garik Israelian and astronomer/musician Brian May, envisioned a week during which anyone could easily attend talks by some of the greatest minds on the planet, touching all the sciences, and also have some good fun with rock 'n' roll. "You have to use both halves of your mind," May, the founding guitarist of the rock group Queen, likes to say.



Armenia's location at the crossroads of Europe and Asia has given it a rich ancient cultural history.

ASTRONOMY: ROEN KELLY

We have just finished the sixth incarnation of Starmus. The festival, which generally happens every other year, has been to the Canary Islands, to Norway, to Switzerland, and, this year, to

Armenia, homeland of Starmus Director Garik Israelian. Some years ago, Israelian and May initiated me into the Starmus Board, and I was astonished this year when they named me its president. Along with May, Israelian, and myself, the board consists of evolutionary biologist Richard Dawkins, microbiologist Emmanuelle Charpentier, astronomer Jill Tarter, musician and humanitarian Peter Gabriel, engineer and entrepreneur Tony Fadell, and astronomer Robert Williams.

Armenian Starmus

Our plan this time carried us through a weeklong adventure in Yerevan, Armenia's capital, which boasts a population of just over a million. The country itself ranges over a mountainous area about

the size of Maryland. Yerevan is one of the oldest continuously populated cities on Earth, and the country's very old history of Christianity and early interest in science have given rise to many unique cultural sites.

You could whisk through Yerevan's cosmopolitan downtown believing you were in part of New York City, with crowds hustling along the sidewalks, shops of all kinds, and modern hotels and cafes. While we began soaking in the atmosphere — and started our battle with jet lag — a new addition to Starmus was up and running. Michael E. Bakich,



STARMUS SPEAKERS AND MORE ...



Garik Israelian, Starmus director and co-founder, opens the festival with a description of all the amazing events to come.



Keyboardist Rick Wakeman, legendary from his days with Yes, opens the concert festivities and entertains the Starmus crowd of 5,000.



Starmus Board member and Nobel Prize winner Emmanuelle Charpentier, celebrated for her coinvention of CRISPR technology, describes the future of genetics.



A Starmus Board member and technical genius, Tony Fadell gets the crowd excited on the first night. Fadell is the inventor of the iPod and the co-inventor of the iPhone.



The History Museum of Armenia shows the stylish architecture of the central area of Yerevan, combining classical looks with a modern city.

contributing editor of this magazine, traveled to Yerevan to run a Starmus Astrophotography School. Along with Scott Roberts, Oshin Zakarian, and Chris Go, he taught the 16 students all manner of techniques for capturing the sky in images.

As the astrophoto school wound down, the main Starmus festival wound up. And, as always, we discovered that despite our best intentions, the Starmus experience is an exercise in sleep deprivation, with activities and catching up with friends beginning in the mornings, cranking up again after the scheduled

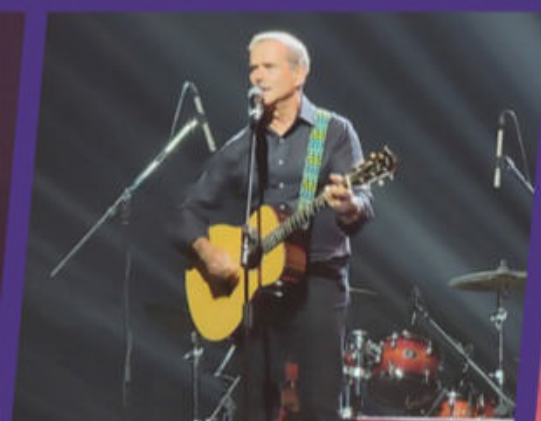
events, and lasting long into the night.

The opening concert on Sunday, Sept. 4, featured remarks by Israelian, followed by a superb lecture on the brain and its function by Edvard Moser, Nobel-Prize-winning neuroscientist and director of the Kavli Institute for Systems Neuroscience in Trondheim, Norway. We then heard terrific music led by keyboardist Derek Sherinian, along with Ric Fierabracci on bass and Simon Phillips on drums. And there were additional concert pieces by Armenian jazz pianist Tigran Hamasyan featuring

bassist Marc Karapetian and drummer Arthur Hnatek. It was a spectacular way to start the week.

The next day, Monday, Sept. 5, was a short day compared with those to come. I commenced by giving the first of four talks I would present around the city, composed of ideas from my 2020 book *Galaxies*; other speakers provided similar talks. We also visited schools and academies and spread the love for Starmus and our enthusiasm for science.

That evening, the momentum ramped up significantly when our arena filled up with the approximately 5,000 Starmus attendees



Always popular, Canadian astronaut Chris Hadfield — one of the nicest guys in the world — wows the crowd by singing his rendition of "Space Oddity."



Artificial-intelligence expert Bernhard Schölkopf describes what is coming in the world of AI.



Graham Gouldman of 10cc and Brian May of Queen knock out several tunes together, including their new song "Floating in Heaven," supported by an all-star backing band.



The world's leading expert on black holes, Kip Thorne, describes these weird entities and their warping of space, assisted by artist and project partner Lia Halloran.

Dear Starmus Festival,

It's Sammy here. I'm not sure if this is a closure or the beginning of a new chapter in my life. You see, I'm a sixth-year medical student in Yerevan, and I was a coordinator for two of your dearest speakers.

The first, David J. Eicher, has inspired millions around the world with his clear communication. And the second, Edvard Moser, is a neuroscientist whose discovery of grid cells – our internal GPS – won him a Nobel Prize.

My time with Prof. Moser was short but filled with discussions. And David was kind enough to guide me into the world of astronomy, introducing me to the greatest minds of science. I was humbled by their genial remarks: "Consider yourself a part of our group now," they all said.

The Starmus Star Party was dazzling. When I viewed Jupiter and Saturn for the first time, I felt a flutter in my chest and a tear in my eye. That night, I dined with matchless men and women of science, and even spoke about such ordinary things as bread to Charlie Duke, one of our last remaining moonwalkers. How many people can say that?

The haziness of my memory and the foggy stages of the Starmus arena produces a dreamy effect. But I'm sure that it was real – because I'm a different person now, having grown in ways I hadn't anticipated.

Sama Shamyar

LETTER TO STARMUS

Sama Shamyar, Persian by heritage and a resident of Yerevan, Armenia, was one of a small army of volunteers who helped to make the sixth Starmus Festival happen. "With all I had to do – press conferences, hosting, off-site talks, and backstage craziness – I certainly wouldn't have gotten anywhere without her assistance," Eicher says.

CARD: ROMAN SAMOKHIN/DREAMSTIME

ABOVE RIGHT: Astronomy Contributing Editor Michael E. Bakich hosted the Starmus Festival on several days, keeping the audience lively with stories and anecdotes.

and we presented a multimedia show, talks, and concert centered on the Stephen Hawking Medals for Science Communication.

Backed by a superlative group that included Rick Wakeman, the greatest keyboard player in the history of rock, and the Armenian Philharmonic Orchestra, we featured tunes by Serj Tankian as well as by the supergroup Sons of Apollo, consisting of Ron "Bumblefoot" Thal, Jeff Scott Soto, Mike Portnoy, Billy Sheehan, and Sherinian.

The medals, in the name of our dear departed Stephen Hawking, who had been on our Starmus Board, went to: May for his tireless promotion of science communication; Jane Goodall, the world's leading expert on chimpanzee behavior; science journalist Diane Ackerman, whose work has appeared in

The New York Times and many other places; and the NASA Office of Outreach and Media.

A second gala night with blistering rock 'n' roll, amazing celebrity speeches (Goodall's remarks on life on Earth brought a few in the audience to tears), and general, good-natured mayhem already had us a bit tired. And then the fun really started.

Tuesday, Sept. 6, saw the main Starmus talks commence in earnest. Board member Tony Fadell, inventor of the iPod and co-inventor of the iPhone, got us started with a high-energy chat about how technologies on Earth and in space are linked. Another board member, Nobel Prize laureate Emmanuelle Charpentier, then described the breakthrough gene-editing techniques she co-invented, known collectively as CRISPR technology.

Next, we heard a variety of talks that opened the mind to

original lines of thinking. The former director general of the European Space Agency, Jean-Jacques Dordain, walked us through an exploration of Earth as a planet and how we humans had better pay attention to many of the things going on now with our home. Bernhard Schölkopf of the Max Planck Institute in Tübingen, Germany, a brilliant authority on artificial intelligence, delivered a fascinating "state of the union" glimpse at AI, and where the reality of its capabilities may not meet our perceptions. And a favorite pal, London-based science comedian and illusionist David Zambuka, delivered a festive round of audience-participation skits, bolstered with a dose of magic tricks.

That evening's gala dinner in the city went well into the night.

The meaning of Starmus

Wednesday's talks took a hard turn squarely into the other





planets of our solar system and beyond. The theme of the conference was “50 Years on Mars,” harking back to the first two successful Mars missions, the Soviet Mars 3 and the U.S. Mariner 9. Lou Friedman of the Planetary Society gave us a superb overview of Mars missions from those early days up to the present. Bethany Ehlmann of NASA’s Jet Propulsion Laboratory provided a tour of the most important scientific discoveries achieved on the Red Planet to date. And Scott Hubbard, Stanford University physicist and former director of

NASA’s Ames Research Center, provided an overview of Mars exploration and where it’s headed.

The afternoon sessions kept right on going with superb lectures: Michel Mayor, Nobel Prize winner for his discovery of the first exoplanet orbiting a Sun-like star, enlightened us with a talk about the billions of planets estimated to inhabit the cosmos. Taking things a step further, Lisa Kaltenegger, director of the Carl Sagan Institute at Cornell University, described alien Earths to the audience, mesmerizing us with the almost limitless

possibilities of what we may discover in the years to come. And then David Grinspoon, planetary scientist and world-leading expert on Venus, issued a warning about climate catastrophes on Venus, Mars, and Earth.

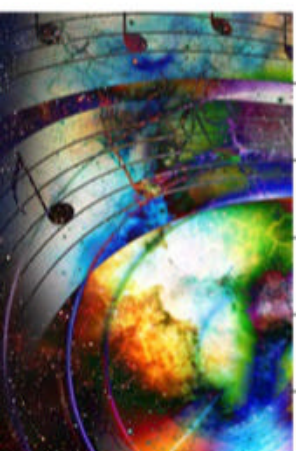
It was an incredible day of dynamic talks. And it wasn’t over yet. The meaning of Starmus began to crystallize: bringing incredible scientific knowledge about our world together with music that allows us to feel the human spirit.

To say that the concert that evening was a mind-blower kind of sells it short. May was joined by his friend Graham Gouldman, the co-founder, bassist, and singer of the group 10cc. Their all-star band also included Sherinian, Thal, Phillips, and Fierabracci. The band wowed the audience with Queen’s “The Show Must Go On,” 10cc’s “I’m Not in Love,” a blazing version of the classic “Smoke on the Water,” and much more. They also played the new

TOP: The Starmus speakers gather for a collective portrait following the main concert night.

ABOVE LEFT: At the outset of Starmus, Board President David J. Eicher holds a press conference to preview the meeting, assisted by astronaut Garrett Reisman, Nobel Prize laureates Emmanuelle Charpentier and Michel Mayor, and multitasking scientist Chris Rapley.

ABOVE RIGHT: The legendary Jane Goodall accepts her Stephen Hawking Medal for Science Communication in a video address that was so thoughtful, it brought many in the audience to tears.



THE MEANING OF STARMUS BEGAN TO CRYSTALLIZE: BRINGING INCREDIBLE SCIENTIFIC KNOWLEDGE ABOUT OUR WORLD TOGETHER WITH MUSIC THAT ALLOWS US TO FEEL THE HUMAN SPIRIT.



ABOVE: An emotional concert moment arrived for many when the children's choir of the Diocese of Tavush, Armenia, sang a medley of Queen songs. They were synced with a video of Freddie Mercury looming over them; when all belted out "We Are the Champions," it captivated the audience.

RIGHT: Among the excursions taken during Starmus was a journey to Erebuni Fortress, a mountaintop stronghold at Yerevan founded in 782 B.C.



song "Floating in Heaven," which May and Gouldman produced this year as a collaboration. And early in the show, the children's choir of the Diocese of Tavush, Armenia, joined the orchestra to sing a medley of Queen songs. With a synced video of Freddie Mercury in the background, the kids caused quite a number of people around me to tear up.

After the show, our heads were spinning — we were at one with the cosmos. And then I was privileged to attend a late-night dinner with May, Israelian and his family, and Apollo astronaut Charlie Duke and his lovely wife Dottie. We talked astronomy and music and so on deep into the early morning hours. Sleep? Who needs it?

Thursday, Sept. 8, brought new themes to the afternoon talks. Space exploration took on a more prominent role. Former NASA astronaut Jim Bagian, who is of Armenian ancestry, delivered a great talk on the medical and physiological challenges lying ahead in human spaceflight, particularly on long missions to destinations like Mars. Wu Ji, former director of the Chinese National Space Science Center, described China's amazing and ambitious space program. Xavier Barcons, director general of the European Southern Observatory (ESO), laid out his thoughts on ESO's first 60 years of discovery and what lies ahead.

The evening sessions were just as enthralling. The world's leading expert on black holes, Caltech's Kip Thorne, walked us through a presentation demonstrating the warped side of the universe. His talk was aided by the wonderful drawings of artist Lia Halloran; the pair are collaborating on an upcoming book. Ackerman, one of our Hawking Medal recipients, reflected on life on Earth and the meaning of the cosmos. Mark Boslough, a Starmus regular and physicist at Sandia National Laboratories, told us about the threats by impacts from space, past and present.

And then we had a truly wonderful experience. Many Starmus participants traveled outside of

STARMUS SPEAKERS AND MORE ...



A highlight of the festival, London-based science comedian and illusionist David Zambuka provides levity in his comic routine, "Are You a Martian?"



Scott Hubbard, Stanford University physicist and former director of NASA's Ames Research Center, describes the present and coming eras of Mars exploration.



At a late-night, post-concert dinner, Brian May chats with Apollo royalty Charlie Duke and his wife Dottie, who had fun recounting Charlie's Apollo 16 experiences.



Clever, witty, and unpredictable, Lisa Kaltenegger, director of the Carl Sagan Center at Cornell University, delivers a superb lecture on alien Earths.

Yerevan to the Temple of Garni, a 1,900-year-old Greco-Roman structure, where we had a magnificent star party. Roberts, CEO of Explore Scientific, had brought a dozen large telescopes to Armenia, and we had happy crowds spying the Moon, Jupiter, Saturn, and a few deep-sky objects, some getting their first-ever look through a telescope.

Though we were exhausted, we carried on. On Friday, I had the good fortune to serve as host for the day on the main stage, a role that my colleague Bakich had also played on a couple of other days. The festival's final day began with a bang: Duke, another old friend and one of the remaining men who has walked on the Moon, described his adventures on the lunar surface as part of the Apollo 16 mission and also recounted his much-celebrated role as capsule communicator (CapCom) — Mission Control's voice to the crew — for Apollo 11. He is a national treasure, and so much fun. Astronaut and engineer George Nield told us about the future of space tourism, which is exploding in momentum and capabilities. The great visual-effects supervisor Paul Franklin, a multiple Emmy winner, then delivered a highly entertaining talk about visual effects and the sciences. And Tony Donne, CEO of EuroFusion, presented "Fusion: Creating a Star on Earth."

We finished with some



memorable moments. Another Starmus regular, Canadian astronaut Chris Hadfield, enthralled the audience with his "Astronaut's Guide to Walking in Space." It's impossible not to be moved by his energy and enthusiasm. And Leon Stok, an engineer at IBM, gave us a glimpse of the future by detailing recent advances in quantum computing.

Once again, Israelian had pulled off the impossible. We were filled with incredible memories of eye-opening talks, superb musical moments that seemed like dreams, and new

acquaintances and friendships that gave us fresh visions of the cosmos.

Starmus left its 5,000 attendees happy and looking forward to infinite possibilities of the future. We will have to see where the festival goes next and when we can make it happen. But one thing is for sure: Starmus will carry on and celebrate the marriage of science and music once again. 🌌

David J. Eicher is editor of *Astronomy* and president of the Board of Starmus, as well as author of 26 books on science and history.

This year, Starmus celebrated its first star party at the Temple of Garni, outside of Yerevan. The 1,900-year-old Greco-Roman structure was a superlative backdrop for solar system and deep-sky observing.



Nobel Prize-winning astrophysicist Michel Mayor discovered the first extrasolar planet orbiting a Sun-like star. Here, he describes the current state of exoplanet studies.



The local organizers of Starmus surprised *Astronomy* Editor David J. Eicher on his 40th anniversary at the magazine, offering a cake and a bottle of gin called "Astronomer."



Mark Boslough of Sandia National Laboratories, an expert on impacts, describes the great collisions Earth has experienced past and present, and what may come in the future.



Planetary scientist David Grinspoon, one of the world's leading authorities on Venus, captivates the audience with a look at climate change on Earth, Mars, and Venus.

SKY THIS MONTH

Visible to the naked eye
Visible with binoculars
Visible with a telescope

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.

BY MARTIN RATCLIFFE AND ALISTER LING



MARCH 2023

Planetary meetings

Jupiter and Venus come close in a conjunction early this month, as they did in the sky above Honolulu in June 2015. DANIEL RAMIREZ



March opens with a stunning pair of bright planets in conjunction in the western sky. Jupiter and Venus hang together in the evening, shining at magnitude -2.1 and -3.9 , respectively. On March 1, they stand a Moon's-width apart, so it's worth getting to a location with clear skies for this conjunction. Two other conjunctions occur this month: between Venus and Uranus, and between Mercury and Jupiter. Uranus is a binocular object high in the southeast among the stars of Aries. Much brighter is Mars in neighboring Taurus, now a receding and fading object but nonetheless a stunning addition to this

region. Mercury and Saturn lie in the morning sky; at first, both are too close to the Sun to

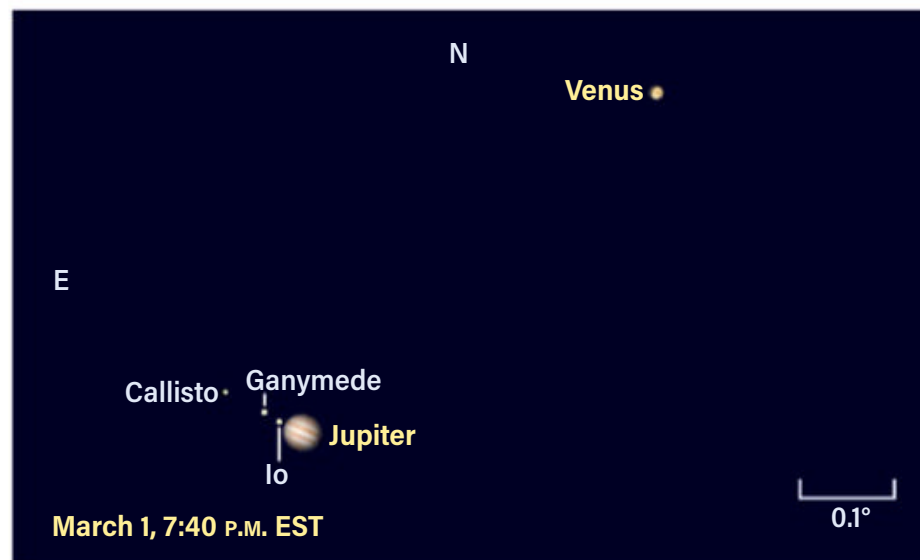
be seen. Mercury transitions to the evening sky in late March.

Let's tour each planet from

sunset to dawn throughout the month. First up is **Venus**, visible even before sunset if you look carefully. As the month opens, Venus is about 30° high in the west. After Venus pops into view in the falling twilight, how long does it take you to spot **Jupiter**, just $30'$ to its southeast? The evening of March 1 in the U.S. is slightly before the true conjunction, which takes place when the giant planet is due north of Venus. That formal moment of conjunction occurs the morning of March 2, well after the pair has set in the U.S.

The contrast of this planetary duo is stunning. Try your first view in twilight before the

Stunning detail   



Venus and Jupiter sit a Moon's-width apart on March 1. A 1° -wide field of view will net both planets, plus three Galilean moons. ALL ILLUSTRATIONS: ASTRONOMY: ROEN KELLY

OBSERVING HIGHLIGHT

JUPITER and **VENUS** kick off March just 30' apart on the first day of the month.



dazzling brightness of Venus overwhelms easy observation of its disk. Use low magnification and aim for about a 1° field of view to see both planets together. Venus, an Earth-sized planet, reveals an 86-percent-lit disk spanning 12". Jupiter is attended by its three of its four Galilean moons; Europa is hidden behind the giant in the early evening and even when it's clear of the limb, it remains within Jupiter's vast shadow. Europa reappears soon after 7:10 P.M. PST for West Coast observers, long after the planet has set for the eastern half of the country.

Venus lies 1.37 astronomical units (127 million miles) from Earth. (One astronomical unit, or AU, is the average Earth-Sun distance.) Jupiter, on the other hand, is nearly five times farther, 5.78 AU (537 million miles) away. Even at this huge distance, Jupiter sports a larger diameter of 34", conveying its true dominant size in our solar system.

Set against the faint constellation Pisces the Fish, there are no other bright stars in this region of the sky. The planetary duo sets before 8:30 P.M. local time. After March 1, the nightly view shows the pair of planets separating. Jupiter continues to fall toward the Sun, so to speak, as it heads for conjunction later in the spring. Venus, on the other hand,

— Continued on page 34

RIISING MOON | More than meets the eye

WHAT CAN COMPARE to the fantastic chain of lunar features along the day-night terminator of a five-day-old Moon? Viewing the lunar surface through a telescope is the closest we're going to get to experiencing Buzz Aldrin's magnificent desolation. On the evening of the 26th, Posidonius and the Serpentine Ridge dominate the northern half, while the bright-rimmed black hole of Theophilus catches the eye at the equator.

The true extent of the mighty blast that carved out the Nectaris basin is revealed at this low Sun angle. The Sea of Nectar is defined by the darker plains of lava that bubbled up from below through the cracks in the basin floor. A feature like this is much more complex than a simple bowl with a central peak and much larger than what first greets the eye.

The true rim of Nectaris stands out in the form of the Altai Scarp, a bright arc that disappears southeastward under the more recent crater Piccolomini. As the Sun continues to rise, the northern part of Altai is slowly revealed over the next hours and appears quite noticeable on the following night.

Reverse lighting occurs when the waning gibbous Moon rises barely before midnight, with the tall rim of the scarp casting stark black shadows. Look on March 10th and 11th to see it, or again on April 9th and 10th.

Altai Scarp



The long, curving Altai Scarp delineates the southwestern rim of Mare Nectaris. CONSOLIDATED LUNAR

ATLAS/UA/LPL. INSET: NASA/GSFC/ASU

METEOR WATCH | Dust causes false dusk

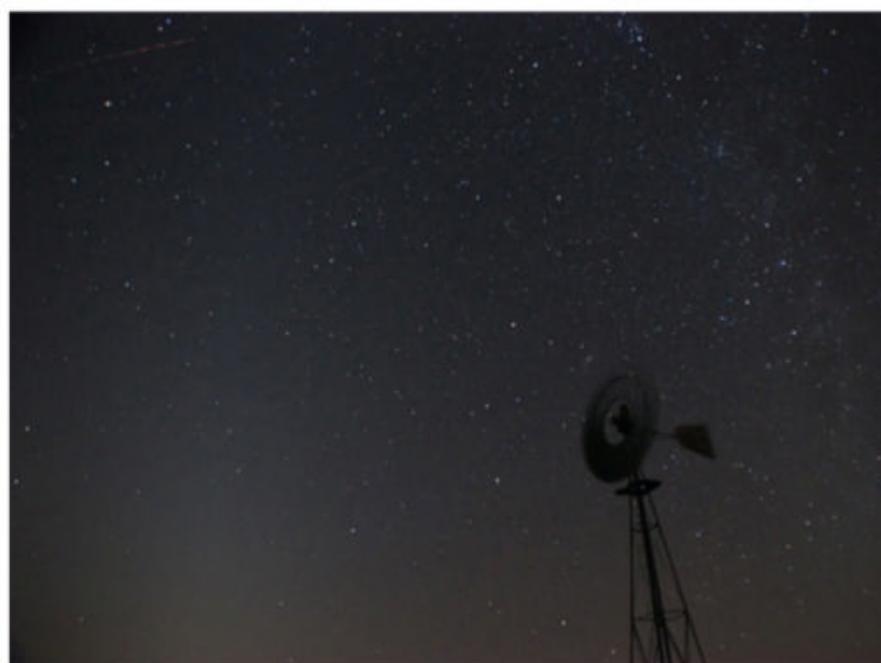
SPRING IS RELATIVELY DEVOID of meteor showers until April, but this lull in activity is replaced by ideal circumstances

to observe the zodiacal light. Our solar system is littered with eons' worth of debris from passing comets. This

dust tends to settle into the orbital plane of the solar system. Well after sunset in March, with the ecliptic angled very steeply to the horizon, this subtle, diffuse light from billions of particles is clear to see from dark locations well away from streetlights.

As the long, low arc of twilight fades across the western horizon, watch for an extended cone of light stretching up through Aries and Taurus, almost as bright as the Milky Way if you're in a dark location. Any cities to your west will obliterate the view. Observers who can reach higher elevations are at an advantage thanks to less atmospheric scattered light, which subdues the zodiacal glow. The best time to look is after the early March Full Moon. Make your attempt between March 10 and 23, which is when the Moon reappears in the evening sky.

Cone of light



The glow of the zodiacal light climbs upward in the west at this time of year. PATRICK DENKER

STAR DOME

HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

10 P.M. March 1

10 P.M. March 15

9 P.M. March 31

Planets are shown at midmonth

MAP SYMBOLS

- Open cluster
- ⊕ Globular cluster
- Diffuse nebula
- ⊛ Planetary nebula
- Galaxy

STAR MAGNITUDES

- Sirius
- 0.0 ● 3.0
- 1.0 ● 4.0
- 2.0 ● 5.0

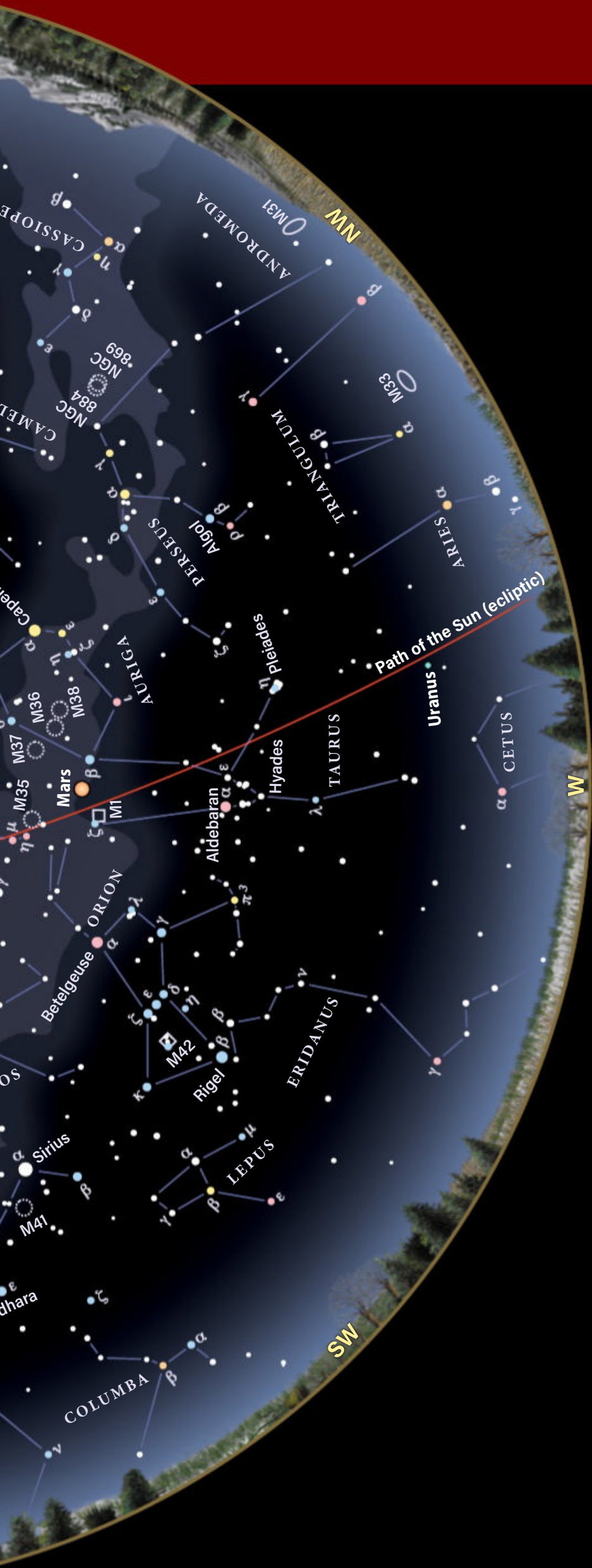
STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light



BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT www.Astronomy.com/starchart.



MARCH 2023

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
						
			1	2	3	4
						
5	6	7	8	9	10	11
						
12	13	14	15	16	17	18
						
19	20	21	22	23	24	25
						
26	27	28	29	30	31	

ILLUSTRATIONS BY ASTRONOMY: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

- 2 Venus passes 0.5° north of Jupiter, 6 A.M. EST
- 3 The Moon is at apogee (252,207 miles from Earth), 1:00 P.M. EST
- 7  Full Moon occurs at 7:40 A.M. EST
- 14  Last Quarter Moon occurs at 10:08 P.M. EDT
- 15 Neptune is in conjunction with the Sun, 8 P.M. EDT
- 17 Mercury is in superior conjunction, 7 A.M. EDT
- 19 The Moon passes 4° south of Saturn, 11 A.M. EDT
The Moon is at perigee (225,369 miles from Earth), 11:12 A.M. EDT
- 20 Vernal equinox occurs at 5:24 P.M. EDT
- 21 Dwarf planet Ceres is at opposition, 4 A.M. EDT
 New Moon occurs at 1:23 P.M. EDT
- 22 The Moon passes 0.5° south of Jupiter, 4 P.M. EDT
- 24 The Moon passes 0.1° south of Venus, 6 A.M. EDT
The Moon passes 1.5° north of Uranus, 9 P.M. EDT
- 28 The Moon passes 2° north of Mars, 9 A.M. EDT
Mercury passes 1.5° north of Jupiter, 11 A.M. EDT
 First Quarter Moon occurs at 10:32 P.M. EDT
- 31 Venus passes 1.3° north of Uranus, 2 A.M. EDT
The Moon is at apogee (251,605 miles from Earth), 7:17 A.M. EDT

WHAT IS AVAXHOME?

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recent software, latest music releases.

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Cheap constant access to piping hot media

Protect your downloadings from Big brother

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18 years of seamless operation and our users' satisfaction

All languages

Brand new content

One site

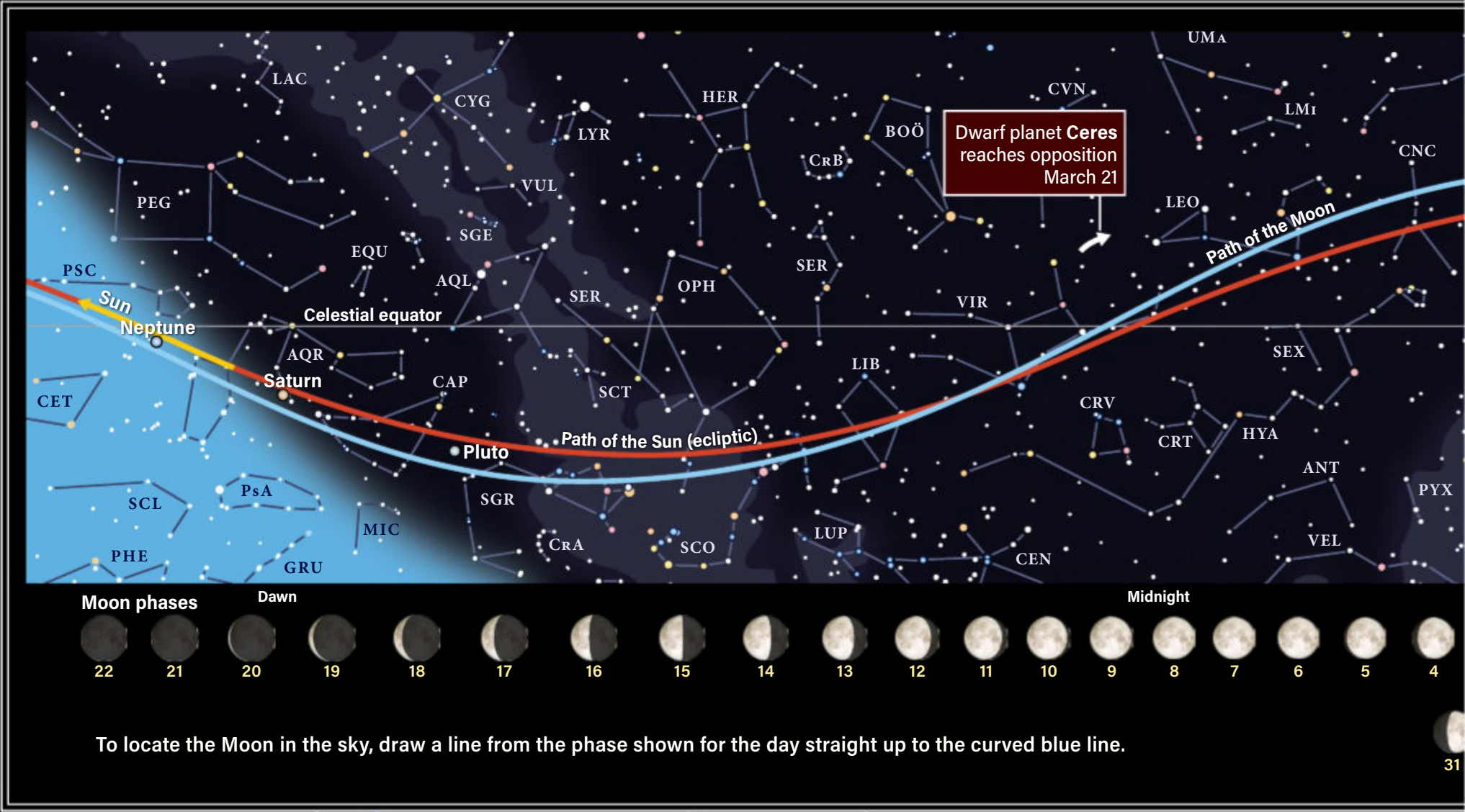


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AvaxHome - Your End Place

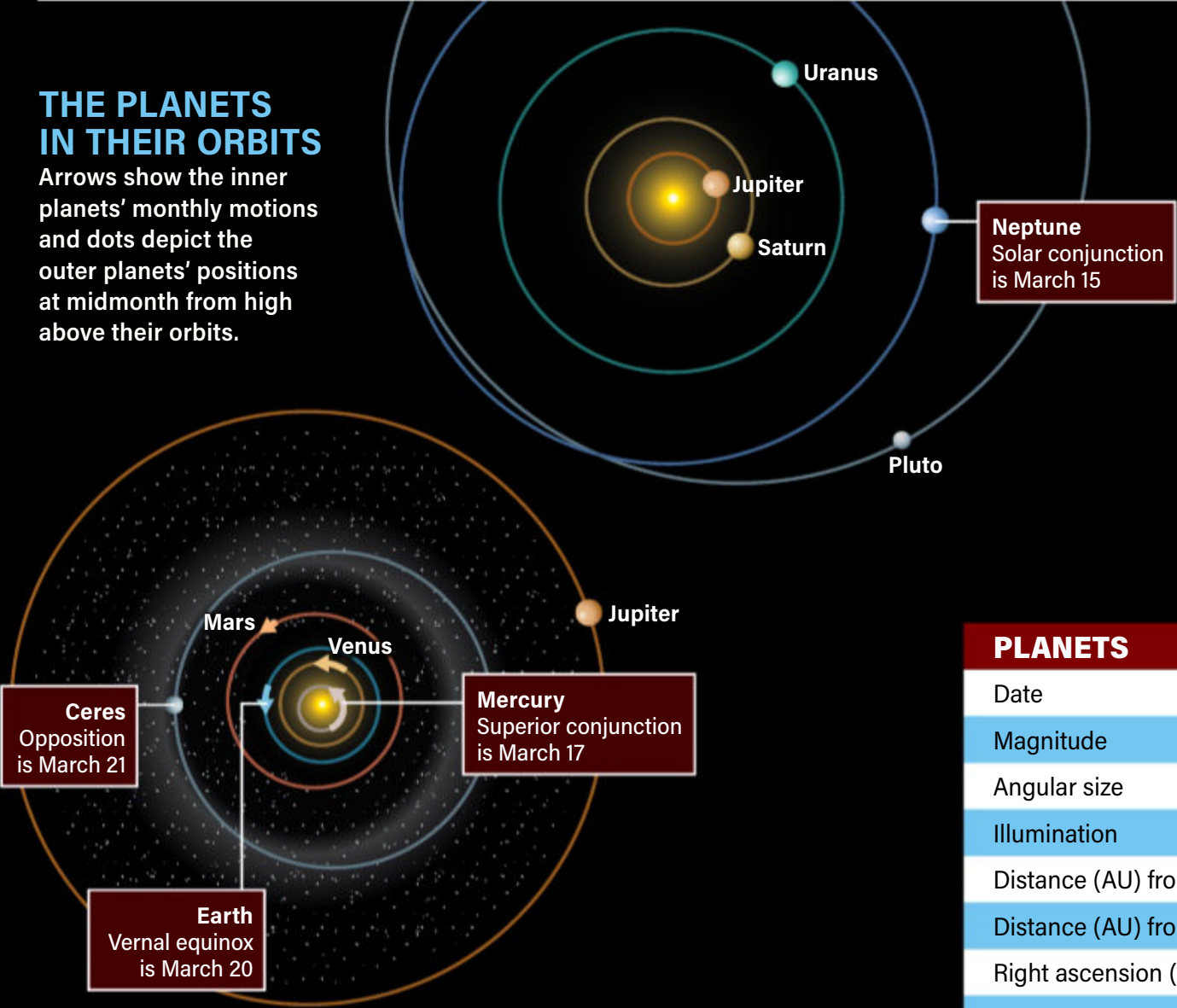
We have everything for all of your needs. Just open <https://avxlive.icu>

PATHS OF THE PLANETS



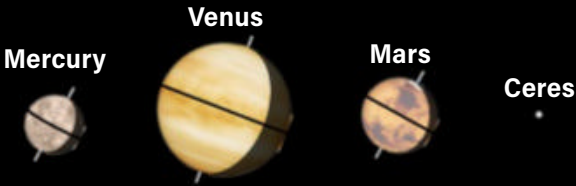
THE PLANETS IN THEIR ORBITS

Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at midmonth from high above their orbits.



THE PLANETS IN THE SKY

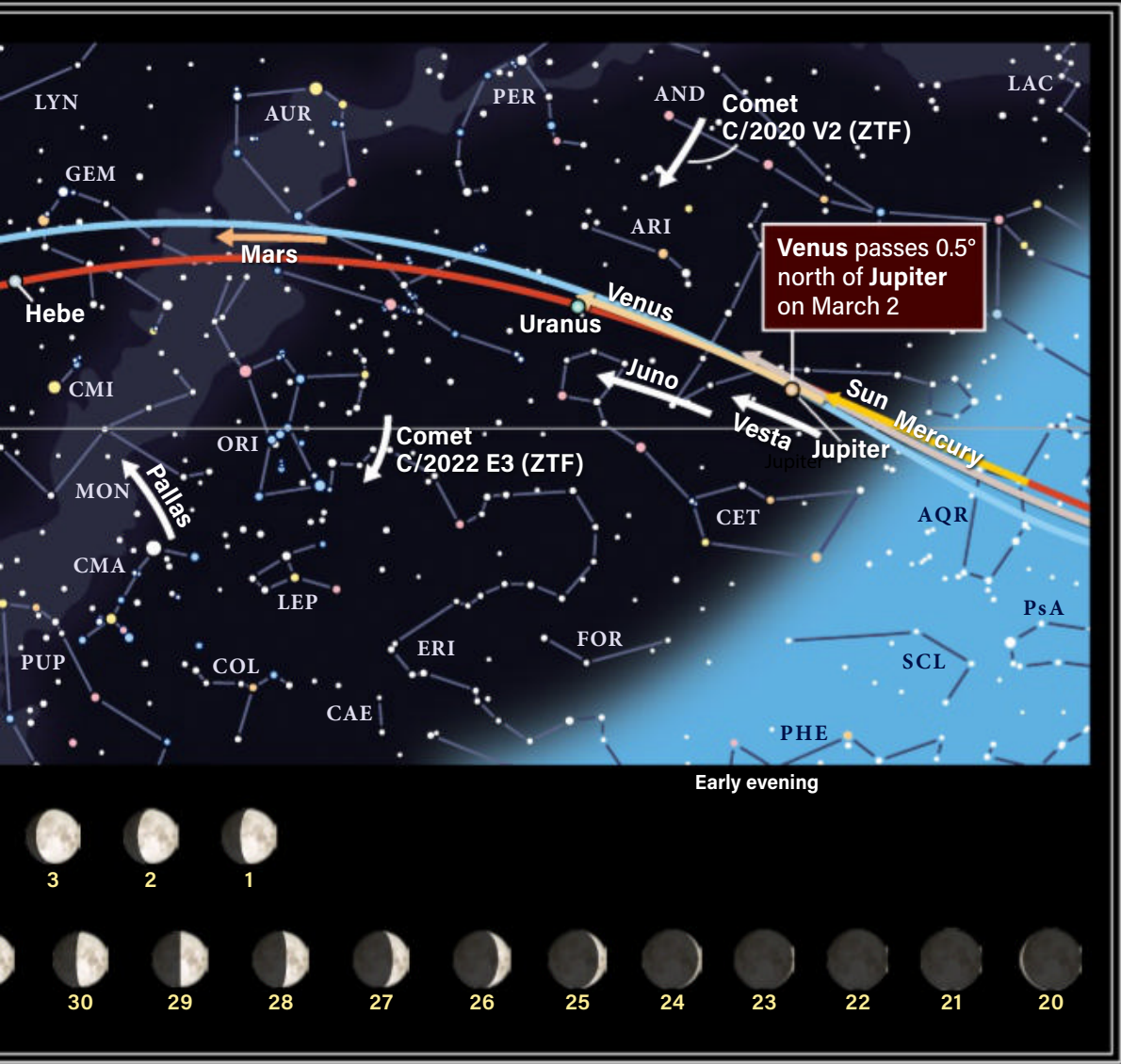
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



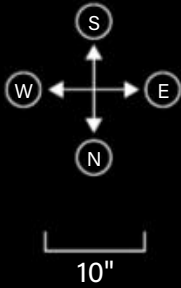
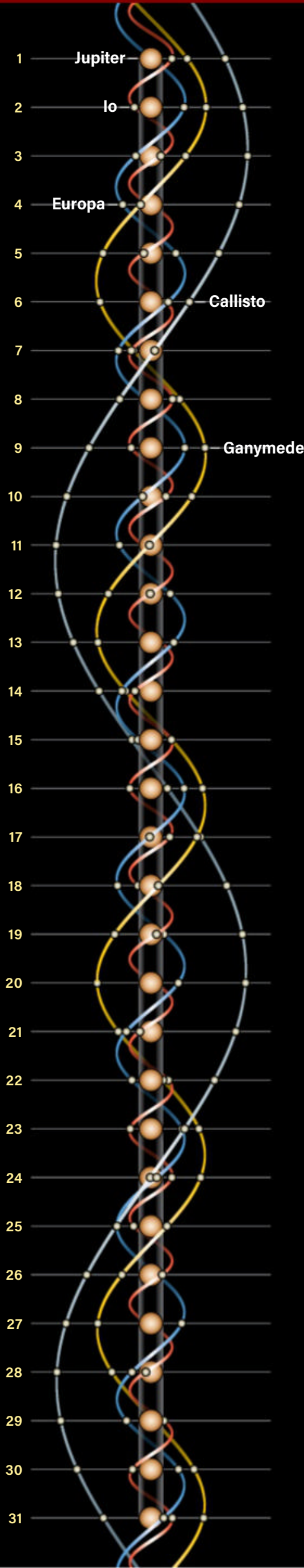
PLANETS	MERCURY	VENUS
Date	March 31	March 15
Magnitude	-1.2	-4.0
Angular size	5.7"	12.9"
Illumination	83%	82%
Distance (AU) from Earth	1.173	1.295
Distance (AU) from Sun	0.308	0.720
Right ascension (2000.0)	1h24.5m	1h41.5m
Declination (2000.0)	9°41'	10°32'

This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.

MARCH 2023



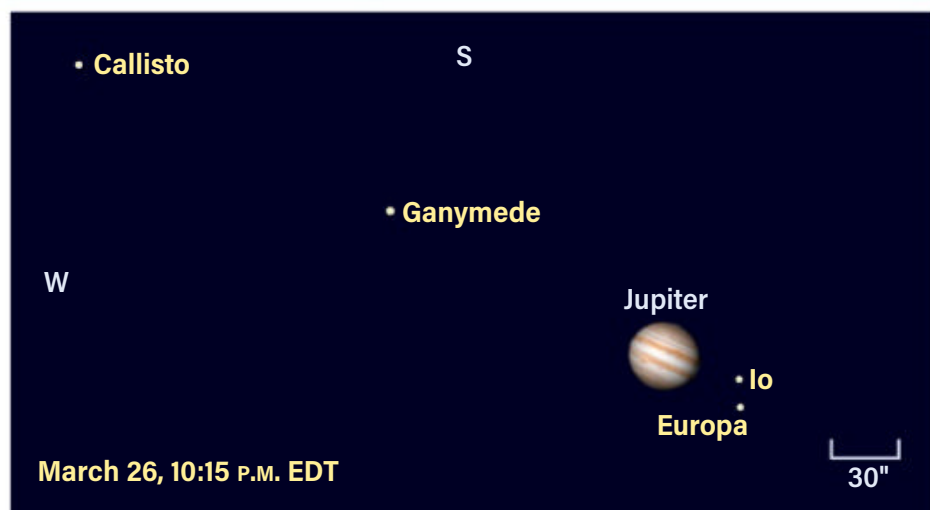
JUPITER'S MOONS
Dots display positions of Galilean satellites at 9 P.M. EDT on the date shown. South is at the top to match the view through a telescope.



MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
March 15	March 15	March 15	March 31	March 15	March 15	March 15
0.7	7.0	-2.1	0.9	5.8	7.8	15.2
7.3"	0.8"	33.6"	15.7"	3.5"	2.2"	0.1"
90%	100%	100%	100%	100%	100%	100%
1.284	1.604	5.867	10.587	20.257	30.905	35.297
1.637	2.566	4.952	9.813	19.659	29.911	34.726
5h36.8m	12h33.2m	0h56.1m	22h19.1m	2h53.4m	23h42.6m	20h08.8m
25°35'	14°52'	4°49'	-11°54'	16°14'	-3°09'	-22°35'

SKY THIS MONTH — Continued from page 29

Up top and down below 🔭



The tilt of the Galilean moons' orbits can create interesting sights. Last month, Callisto and Ganymede appeared to pass one over the other. This month, Europa crosses 13" north of Io.

continues to climb and extends its angular separation from our star. By midmonth, it crosses into Aries the Ram.

Look low in the west on March 22 for Jupiter and a crescent Moon, less than 2° apart. They set about 70 minutes after the Sun. The following evening, the Moon hangs 6° below Venus in another lovely pairing. Try photographing this scene in twilight with interesting foreground objects to create an artistic silhouette against the sky.

As a prelude to the Venus-Uranus conjunction, the wandering crescent Moon and **Uranus** stand less than 1.5° apart on March 24. Grab binoculars to view the lovely crescent Moon, then scan southward to find the dim planet shining at magnitude 5.8. Uranus is close to a 7th-magnitude field star just 4' away. Attentive observers in some U.S. locations will spot the disappearance and reappearance of 6th-magnitude Rho (ρ) Arietis in an occultation by the Moon that takes place from approximately 7:30 P.M. to 8:10 P.M. local time. (You'll want to check precise predictions, as whether the event is visible and its exact

timing are affected by your geographic location.)

By March 30, Venus is in conjunction with Uranus. With binoculars, you can find Uranus standing 1.2° due south of Venus. Venus now shows a 78-percent-lit gibbous disk

spanning 14". The much more distant Uranus (20.45 AU; 1.9 billion miles) spans 3". The following night, the last evening of March, the two planets are still less than 2° apart. They set before 10:30 P.M. local time, so plan your viewing soon after dark.

Uranus is an easy binocular target all month, starting March near Sigma (σ) and Pi (π) Arietis, a pair of 5th-magnitude stars about 12° due north of Menkar in Cetus the Whale. On March 1, the planet is located midway between these two stars; from night to night, it wanders northeastward. It passes close to a 6th-magnitude field star on March 15, then enjoys its

WHEN TO VIEW THE PLANETS

EVENING SKY

Mercury (west)
Venus (west)
Mars (southwest)
Jupiter (west)
Uranus (west)

MIDNIGHT

Mars (west)

MORNING SKY

Saturn (east)

meeting with the Moon on the 24th and with Venus on the 30th.

Mars blazes brightly in Taurus the Bull, outshining magnitude 0.9 Aldebaran for most of March and ultimately fading to match the red giant

28.5° Between March 1st and 31st, Venus and Jupiter separate by 28.5°.

COMET SEARCH | Bewitched by the green glow

PICTURE A DOLPHIN jumping over the back half of your cruising boat and diving deep — that trajectory is similar to Comet C/2022 E3 (ZTF)'s passage by Earth. We rapidly turn our gaze at first, then almost stop panning as we watch it fade into the depths.

Last month's peak performance is done, but it's not the end of the show. ZTF displays a broad but short diffuse fan of dust spreading northward, with a sharp southern flank. Before moonrise on the evening of March 10, the comet is a mere 10' from the star-filled spiral galaxy NGC 1637. The next night, it's still on the edge of a medium-power eyepiece field centered in the same spot. Compare and contrast their shapes and the distribution of their light under country skies with a 6-inch or larger scope. Which of these 10th-magnitude objects is brighter?

West of Orion's blazing foot Rigel, ZTF descends between 4th-magnitude Mu (μ) and Nu (ν) Eridani, curling toward the famous Witch Head Nebula (IC 2118). The green glow of the comet's coma punctuates a 6°-wide-field shot here during New Moon.

Comet C/2022 E3 (ZTF) 🔭

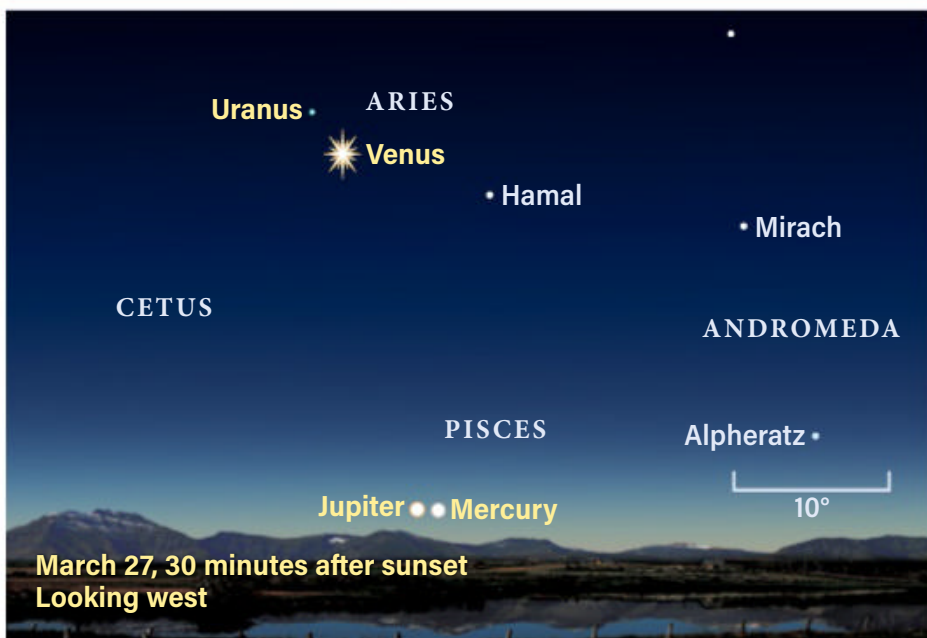


Comet ZTF zooms through a rich region of sky this month, headed for the Witch Head Nebula near Rigel.

LOCATING ASTEROIDS I

Sirius won't fetch Pallas

Musical planets



Jupiter leaves Venus behind to mingle with Mercury late in the month. Observers will need binoculars or a small scope to spot Uranus.

star by the end of the month. The Red Planet's nightly path carries it roughly midway between the horns of the Bull, marked by the stars Zeta (ζ) and Beta (β) Tauri, on March 11. It crosses into Gemini March 26.

In the first week of March, Mars spans 8". During this week, the features facing earthward around midevening include the Tharsis ridge and Olympus Mons. By mid-March, the planet has shrunk to 7" and Valles Marineris and Solis Lacus are prominent. In the third week of March, Sinus Meridiani and Sinus Sabaeus are on display.

On March 29, Mars stands 1.1° due north of the fine open star cluster M35 in Gemini. The view in binoculars is worthwhile, and a rich-field telescope reveals a star-studded field of view along with the brilliant orange glow of Mars, now magnitude 0.9. The prominent dark feature Syrtis Major is coming onto the Earth-facing disk at the end of March during early evenings.

The best views of Mars occur a couple of hours after sunset, with Mars very high in the sky. By the end of March, Mars sets before 2:30 A.M., allowing ample time for observers to test their skills on a tiny disk.

Hours pass between when Mars sets and another planet appears in the sky. **Mercury** is a difficult object in the morning sky in early March. On March 2, it's in conjunction with Saturn, which is reappearing after last month's solar conjunction, but the event won't be visible for most observers in North America. Mercury shines at magnitude -0.6 and Saturn is fainter at 0.8 . The difficulty is that this conjunction takes place only 13° west of the Sun when the ecliptic is at a low angle to the horizon; furthermore, the pair rises less than 20 minutes before the Sun, rendering the sky too bright to see them.

Mercury sinks toward its March 17 conjunction with the Sun and reappears in the evening sky in a more favorable

THE CELESTIAL DOG Canis Major pays no attention to the modestly bright 8th-magnitude starlike dot passing north of its blazing heart, Sirius. The second asteroid to be discovered, 2 Pallas tracks into Monoceros the Unicorn after midmonth. On your way to observing our main-belt target, stop by the star clusters M50 and M41 (the latter is just south of this field of view; see last month's chart).

A 4-inch scope from the suburbs will readily reveal Pallas, but your go-to scope might land you on a field with quite a few stars. Which one is the impostor? The tried-and-true method is to make a quick four-star sketch and come back two hours — or one or more nights — later to see which one shifted. On the positive side, there are many nights where Pallas is the brightest object in the field.

Did you know that asteroids commonly masquerade as supernovae? Tracking across Coma Berenices, 1 Ceres skims the outskirts of galaxy M91 on the 11th, then slides across the arms of the open-face spiral M100 on the 26th. Both galaxies lie far beyond the Milky Way itself, in the Virgo Cluster. We'll feature the brighter Ceres for a few months beginning in April.

Passing the pooch



Pallas swings up through Canis Major and into Monoceros this month, making its way amid scattered dim stars.

apparition where the ecliptic is steeply inclined to the western horizon. Look for it March 27 some 30 minutes after sunset, shortly before its near conjunction with Jupiter occurs. Mercury shines at magnitude -1.5 and Jupiter, located 1.3° to its right (northwest), is still magnitude -2.1 . The two stand just 3.5° high and set within 20 minutes. Find a location with a horizon that is clear of obstructions such as trees and buildings for a good view of this conjunction.

Saturn, meanwhile,

continues to extend its angular separation from the Sun and by March 31 rises 75 minutes before dawn. You'll find it low in the east an hour before sunrise, now located in Aquarius.

Neptune is not visible this month and passes through solar conjunction on March 15. ☾

Martin Ratcliffe is a planetarium professional with Evans & Sutherland and enjoys observing from Salt Lake City. **Alister Ling**, who lives in Edmonton, Alberta, is a longtime watcher of the skies.



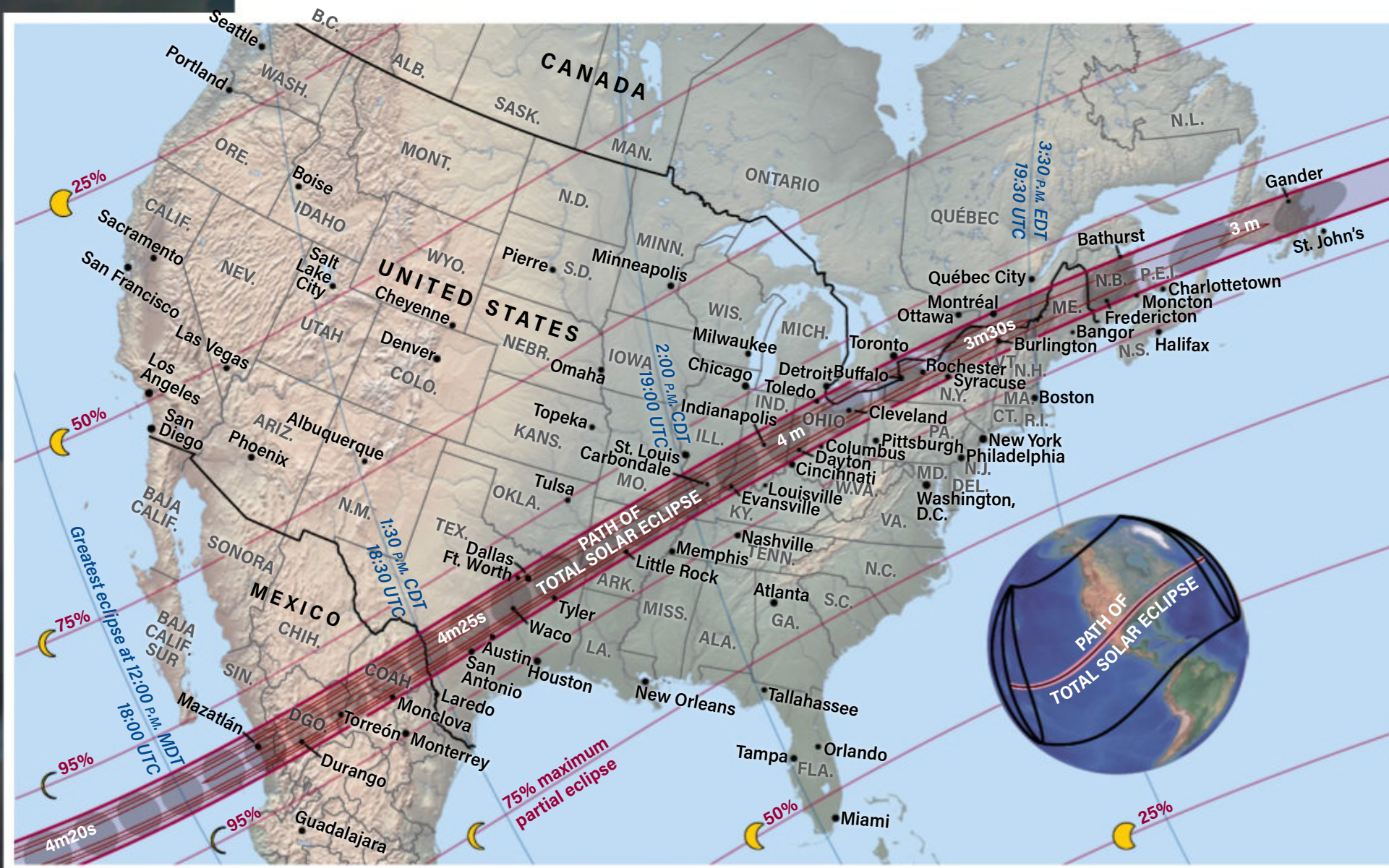
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Plan for the **2024 TOTAL SOLAR ECLIPSE**

On April 8, 2024,
totality will sweep
across North America.
Are you ready for it?

BY MICHAEL E. BAKICH



ASTRONOMY: ROEN KELLY AFTER MICHAEL ZEILER



The Great American Eclipse drew millions to totality in 2017. Don't miss your chance to experience it again in 2024. JIM SCHAFF

MILLIONS OF PEOPLE throughout the U.S. experienced the much-anticipated total solar eclipse of Aug. 21, 2017, the first to cross the country since 1979. And, if you saw the 2017 eclipse, you're no doubt already planning to head to the path of totality when the Moon's shadow again crosses the contiguous 48 states on April 8, 2024.

If you skipped the last one, keep in mind that there won't be another cross-country eclipse for two decades — don't miss out this time!

The nitty-gritty

Every eclipse has a different length of totality. This is caused by the nature of the cosmos as Earth and the Moon orbit not in perfect circles, but ellipses — so Earth is not always the same distance from the Sun and the Moon is not always the same distance from Earth. The result is that the longest possible duration of totality is 7 minutes 32 seconds.

The eclipse on April 8, 2024, won't come close to that. But any period of time under totality is worthwhile — especially this eclipse's maximum of 4 minutes 28 seconds. That duration will occur beginning at 1:15 P.M.

Mexican Central Daylight Time near Nazas, Mexico, a town of nearly 4,000 residents.

In the U.S., the narrow path where totality occurs runs from the Texas-Mexico border through the Maine-Canada border. Everyone in the contiguous U.S. not

within the path of totality will see at least a 16-percent partial eclipse. And while that may sound cool, it doesn't compare to 100 percent.

When the Moon slides into place over the face of the Sun, hazy darkness covers the ground while a beautiful 360° sunset colors the horizon. But



A series of exposures taken over two minutes reveals fine structures and curved lines in the Sun's corona that you would otherwise be unable to see. MIGUEL CLARO

your eyes will be locked high above you on two diamond rings, a glorious corona, and planets (possibly a few stars, too) visible in the daytime.

Save the date

The first to see the Moon's shadow is a region just north of Penrhyn Island — one of the Cook Islands in the South Pacific. But the location will only see a 98.5-percent partial eclipse. The real show starts at 11:51 A.M. MDT, when totality strikes Isla Socorro, Mexico. If this small volcanic island is your frontrunner for eclipse viewing, be sure to do so at the island's southeastern tip. That way you'll enjoy 3 minutes 37 seconds of totality.

A few more islands are blessed with Luna's shadow before it finally encounters the continent southeast of Mazatlán, Mexico. Mazatlán will have about 4 minutes 20 seconds of totality.

However, if you're looking for the greatest duration of totality, head to Nazas. There,

Astroimagers often create composite shots showing the progression of the eclipse. CHIRAG UPRETI

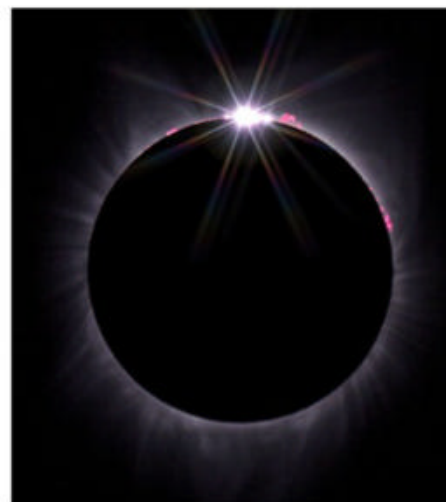
The next eclipse that comes close to the longest possible totality — falling just a few seconds short — will occur July 16, 2186.

viewers will enjoy a grand total of 4 minutes 28 seconds. Though, if you're willing to lose up to a second or so of totality, you can position yourself anywhere along the 550-mile (885 kilometers) center line in Mexico to enjoy this cosmic event.

Moving north

Although Mexico has the greatest duration of totality, U.S. views certainly won't disappoint, especially for those living in the Lone Star State. Most of you won't have to travel at all to see the eclipse. Talk about convenient! But even so, a short journey closer to the center line is certainly worth it.

Moving across the Rio Grande, the shadow touches the community of Radar Base starting at 12:10 P.M. CDT. Totality kicks off roughly an



Pink prominences and diamond rings sparkle as the Moon slots into place over the Sun in 2017. JOHN CHUMACK

hour and 20 minutes later, lasting for 4 minutes 27 seconds. Not to be left out, San Antonio, Austin, Waco, Dallas, and Fort Worth all lie under the shadow. While none of those cities are on the center line, more than 11 million residents in Texas alone will have easy access to an eclipse.

From there the shadow continues through Oklahoma,

Arkansas, Missouri, Illinois, Kentucky, Indiana, Ohio, Pennsylvania, New York, Vermont, New Hampshire, and Maine.

If you're looking to return to your viewing location from the 2017 eclipse, Carbondale, Illinois is once again under shadow in 2024 — though to get the most bang for your buck, Makanda, which lies just to the south, has a slightly longer duration at 4 minutes 10 seconds of totality. Before you choose Illinois as your prime location, however, a word of caution: The likelihood of clear skies there in April are not nearly as great as they are in August.

Ultimately, if you can swing it, traveling southwest increases both your time with totality and your chances of seeing the 2024 eclipse.

Of course, remember that the only statistics we have for now are general ones, averaged over a number of years. The weather on April 8 in a specific location doesn't have to follow the climate trends. It might be clear throughout Maine and cloudy throughout Texas. Probably not, but be sure to monitor the weather at your chosen location starting around April 1.

Plenty of other major cities also lie in Luna's path, including Little Rock, Arkansas; Cleveland, Ohio; and Montréal, Québec. In total, a staggering 31.5 million people are estimated to live within the path of totality. And an additional 117 million reside within 200 miles (322 km) of that line. So, get to your chosen location as early as you can and don't be in a rush to leave post-eclipse.

A few highlights and fumbles

As you might imagine, the



eclipse also will pass over quite a few national treasures, some built by humans and others natural. Photographers near those sites will have opportunities to capture both an earthly and celestial wonder.

Starting with a location that already has an astronomical heritage, some observers may choose to take in the eclipse from Allende, Coahuila de Zaragoza, Mexico. It was there and in the surrounding area on Feb. 8, 1969, that a fireball moving southwest to northeast lit up the sky and exploded, raining thousands of meteorites onto the landscape. And not just any meteorites: These were a rare type called carbonaceous chondrites, some of the most primitive known. In fact, scientists estimate that the Allende meteorite formed 30 million years before Earth. On eclipse day, residents and visitors to this historic site will experience 4 minutes 23 seconds of totality.

The Alamo might have been this eclipse's No. 1 tourist attraction. Unfortunately, the event there is only a 99.941-percent-partial eclipse. That amount of coverage of the Sun's surface by the Moon might sound like it's enough, but at that percentage, your surroundings would be 5,900 times as bright as a Full Moon night. You'll want to drive several miles to the west to experience the grandeur (and safety) of totality.

But one hot spot could be AT&T Stadium in Arlington, where totality will last 3 minutes 17 seconds. The Dallas Cowboys play their home games here. Because the facility has a retractable roof, many of its 80,000 seats will have a great view of the



ABOVE: Remember to keep your eclipse glasses on until the Sun is completely covered by the Moon. If you don't want to wear them while you wait, you can use a setup like this to track Luna's progress. **DAN GORDON**

RIGHT: Don't give up if on the day of totality, the weather forecast isn't ideal. You might get lucky yet! **DOUG MILLAR**

eclipse, which will stand 65° above the horizon at maximum. I don't know if the owners plan to open the stadium for the eclipse but, with seats for tens of thousands of people, it would create one amazing experience.

St. Louis, with a 99-percent-partial eclipse, is another near miss. Too bad, because a shot of the event behind the Gateway Arch would be gorgeous. On the other hand, Indianapolis is right in the middle of the path. Fans of motor sports might want to capture the event with the Indianapolis Motor Speedway's iconic Pagoda scoring tower and Yard of Bricks as their foreground setting.

The next major city covered by the lunar umbra is Cleveland. If weather prospects were better, I'd consider heading there, setting up a sound system in the parking lot of the Rock & Roll Hall of Fame, and watching the eclipse (3 minutes 51 seconds



of totality with the Sun 49° high in the southwest) with Pink Floyd's "Dark Side of the Moon" playing in the background. If you'll be in Cleveland, you might want to photograph the facility beneath the hidden Sun.

And, for anyone willing to gamble, the most picturesque images of the event might come from Niagara Falls — provided, of course, that the northeastern U.S. has good weather on eclipse day. From the outlook called Terrapin Point, an eclipse watcher will enjoy 3 minutes 28 seconds of totality. Almost as important, the Sun will hang 46° high in

the southwest — directly over the Falls!

Last call

This eclipse is a must-see for anyone who isn't a dedicated eclipse chaser. If you miss it, you'll have to wait two decades for another truly spectacular show in the U.S. At least the Aug. 12, 2045, eclipse will be worth the wait with a maximum of 6 minutes 6 seconds of totality.

But anyone who viewed the 2017 eclipse won't need any convincing to see another in 2024. It's a sight you'll never forget. Here's hoping for clear skies! ☿

Michael E. Bakich is a contributing editor of *Astronomy*. The 2024 event will be his 15th total solar eclipse.

A history of SOLAR ECLIPSES

Eclipses have held sway over humanity since long before we knew what these events truly were. **BY MICHAEL E. BAKICH**

AS HUMANS HAVE EVOLVED ON EARTH, many naturally occurring events — earthquakes, volcanoes, destructive weather — have struck fear into their hearts. At the top of the list, I contend, is the disappearance of the life-giving Sun from the midday sky during a total solar eclipse. Even today, the drama of such phenomena compels people to travel halfway around the globe to witness them. But which eclipses throughout history are the most noteworthy?

For this list, I've chosen to include eclipses you might not be familiar with, including many that happened before the invention of the telescope. As you read through them, particularly the earliest accounts, try to imagine standing in darkness beneath the Moon's shadow for a few fleeting minutes — which, in the minds of those terrified souls, must have seemed much longer.



ABOVE: Johann Julius Berkowski is credited with taking the first daguerreotype of a total solar eclipse, during totality in July 1851. His original 84-second exposure has been lost, but the image above is either an 1891 photograph of the daguerreotype or a copy made from an 1854 engraving. JOHANN JULIUS BERKOWSKI/WIKIMEDIA COMMONS

RIGHT: Antoine Caron's *Dionysius the Areopagite Converting the Pagan Philosophers* was likely inspired by a solar eclipse in 1571. It shows Dionysius (in red) flanked by astronomers, as background figures stand in awe or run in fear.

ANTOINE CARON, COURTESY OF THE J. PAUL GETTY MUSEUM COLLECTION

The earliest records

Our first entry is the earliest solar eclipse for which we have a record. The account appears in the ancient Chinese text *Shujing*, traditionally said to have been compiled by the philosopher Confucius, which reads: “On the first day of the last month of autumn, the Sun and Moon did not meet harmoniously in Fang.” What an understated way to describe an eclipse!

Pinning the exact date of this event is somewhat problematic; originally, scholars stated it occurred either in 2136 B.C. or 2128 B.C. The mention of “Fang,” though, ultimately holds the key: This term refers to a section of the sky mainly in Scorpius. Furthermore, we know the eclipse happened during the reign of Zhong Kang, an emperor of the Xia Dynasty. Based on these details, the only eclipse that could have been seen from the capital city was Oct. 22, 2137 B.C.

There's also a long-standing tale — which may be true but very probably isn't — about this eclipse and two royal astrologers, He and Ho. In at least one version, they were drunk prior to the event and didn't



warn the emperor that the eclipse was coming. Whether or not they even knew it was coming is debatable. Long story short, they reportedly were killed for their mistake.

Our next entry is recorded in the *Shijing*, a collection of ancient poetry whose compilation is also credited to Confucius. The eclipse in question occurred during the Zhou dynasty, though the exact date is uncertain. Some astronomers have pointed to the total eclipse of June 4, 781 B.C., though this would have only been a partial eclipse in Zhou territory. Another candidate is the eclipse of Nov. 30, 735 B.C., which was annular in the Western Zhou capital of Hao, near modern-day Xi'an.

About the same time in Greece, Plutarch writes about an annular eclipse that occurred around the death

of Romulus in 716 B.C. Such an eclipse happened Dec. 10. The path of annularity crossed northern Africa, while in Athens, a bit more than one-third of the Sun was obscured by the Moon.

More than a century later, a total solar eclipse May 28, 585 B.C., might have ended a war between the Lydians and the Medes. Greek historian Herodotus wrote about the conclusion of the conflict in Book I of his *Histories*: "As the balance had not inclined in favor of either nation, another engagement took place in the sixth year of the war, in the course of which, just as the battle was growing warm, day was suddenly turned into night. ... When the Lydians and Medes observed the change they ceased fighting, and were alike anxious to conclude peace."

A later solar eclipse had a similar

effect when it cast a shadow on a conflict over Corinth between the Spartans, led by Cleombrotus, and the invading Persians, led by Xerxes I. Herodotus wrote that, "while [Cleombrotus] was offering sacrifice to know if he should march out against the Persians, the Sun was suddenly darkened in mid-sky." As you might imagine, some 2,500 years ago, eclipses were not seen as good omens. This one, which astronomers now think occurred Oct. 2, 480 B.C., rattled Cleombrotus and caused a full retreat of the Spartan forces.

Nearly half a century later, a solar eclipse nearly stopped the army of Athens from attacking the Spartans. In his *History of the Peloponnesian War*, Greek historian Thucydides writes, "in the same summer, at the beginning of a new lunar month (at which time alone the phenomenon seems possible) the Sun was eclipsed after mid-day, and became full again after it had assumed a crescent form and after some of the stars had shone out." This eclipse best matches one on Aug. 3, 431 B.C. From northern Greece, the Moon would have covered more than 91 percent of the Sun. The "stars" that shone out were almost certainly Venus, which was 20° from our daytime star, and Jupiter, which was twice as far away from the eclipsed Sun.

The first millennium

Shortly after B.C. became A.D., a record of a notable solar eclipse comes to us from a work titled *Contra Celsum* by the theologian Origen of Alexandria. In it, he writes of an eclipse that occurred during the reign of Tiberius Julius Caesar Augustus. He states that there was "the greatest eclipse of the sun" and also that "it became night in the sixth hour of the day [noon] so that stars even appeared in the heavens. There was a great earthquake in Bithynia, and many things were overturned in Nicaea."

This event transpired Nov. 24 in the year 29. Some theologians have speculated that this eclipse may have caused the darkness, as described in the Bible, during the crucifixion of Jesus Christ. However, the eclipse was

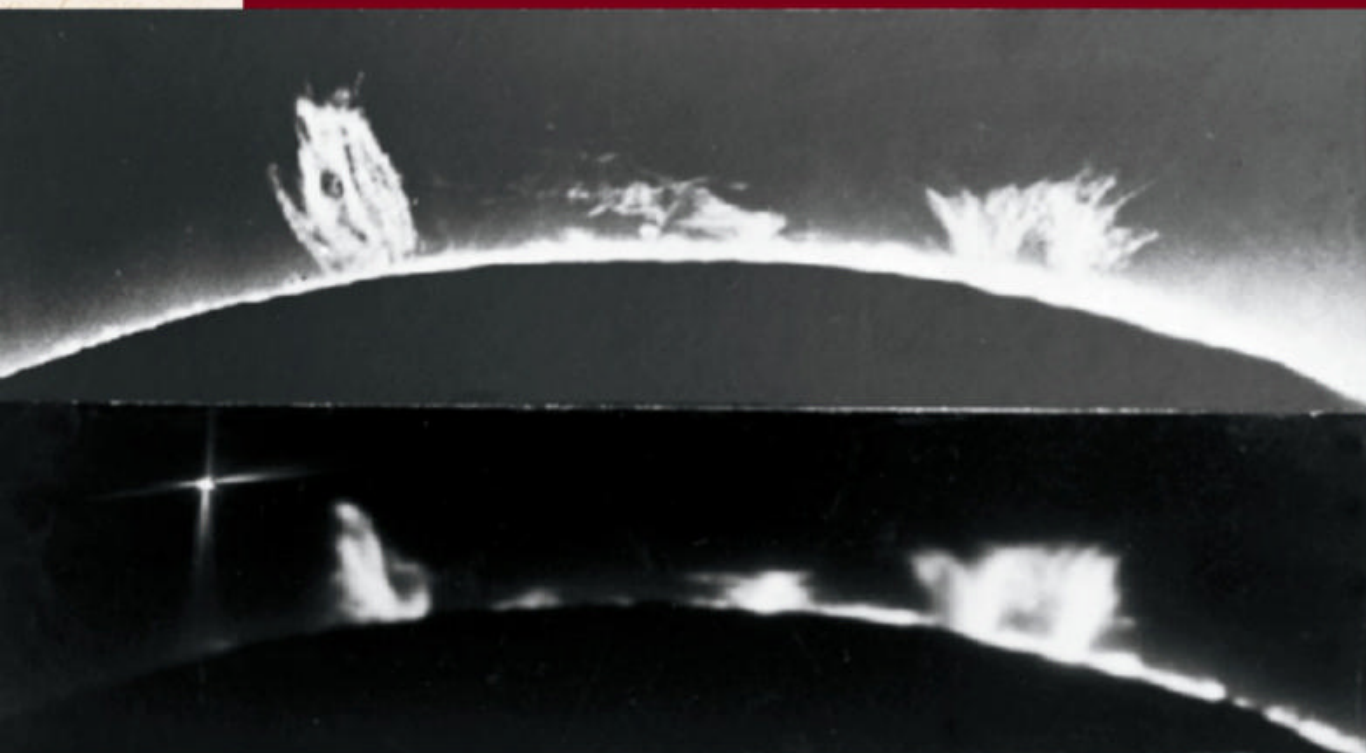


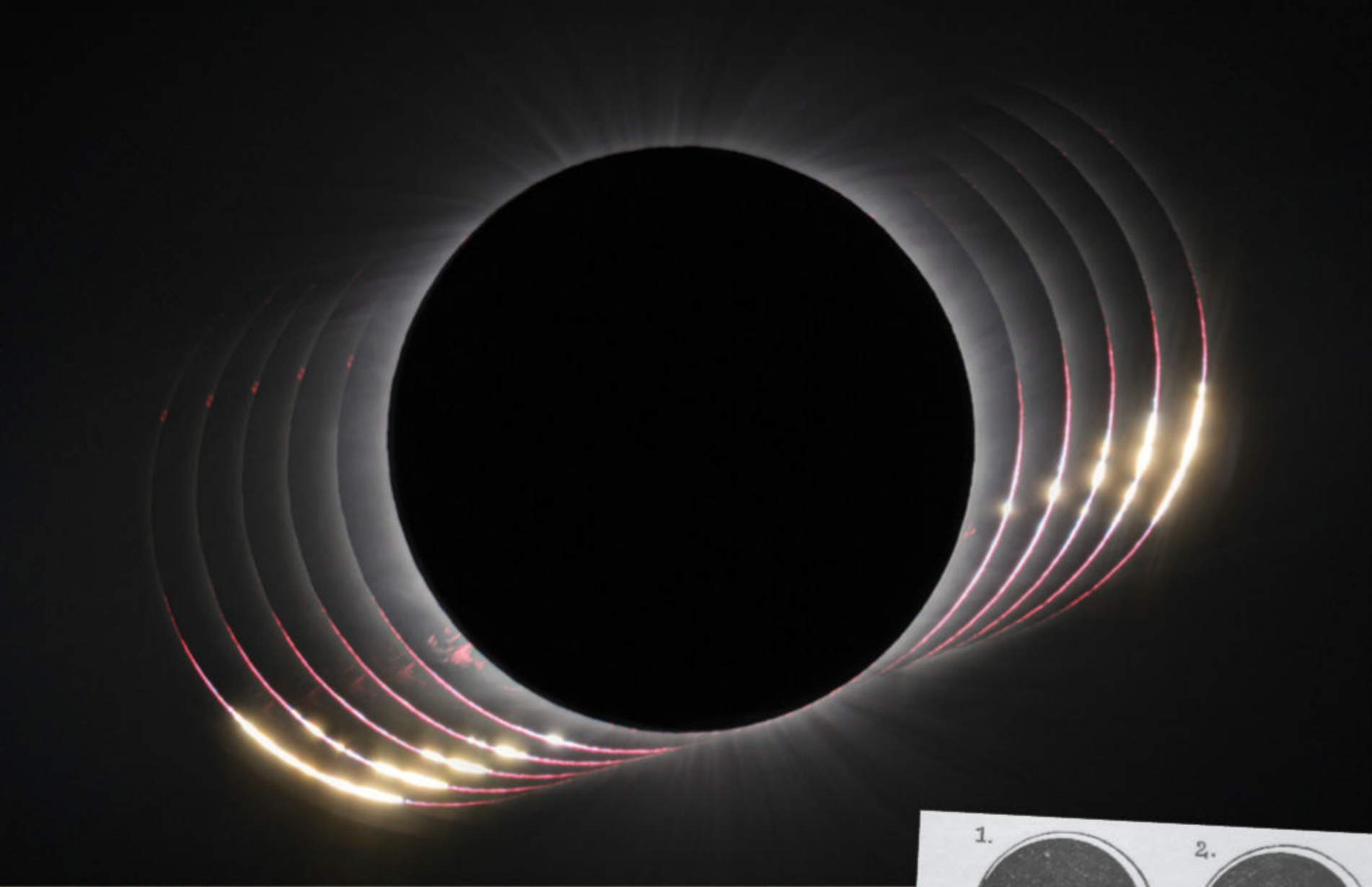
LEFT: This engraved plate made by William Henry Wesley from Arthur Schuster's photographs of the May 17, 1882, eclipse appears in Mabel Loomis Todd's *Total Eclipses of the Sun*. It shows the comet Schuster discovered in the corona during totality.

COURTESY OF SCIENCE HISTORY INSTITUTE

BELOW: Solar prominences seen May 28, 1900, by the eclipse expeditions carried out by Yerkes Observatory and the Royal Observatory, Greenwich, are highlighted in these photos. HANNA HOLBORN

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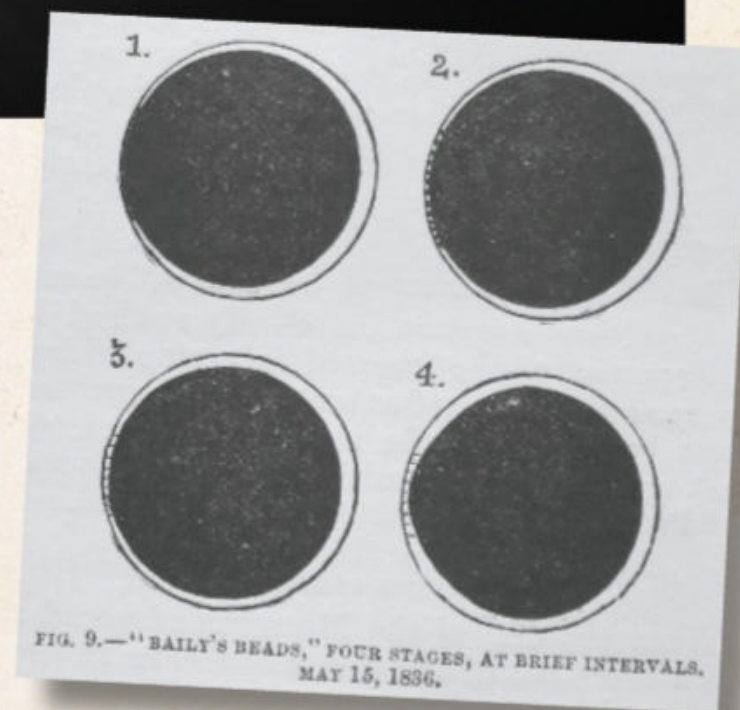
Baily's beads are created by mountains and valleys on the lunar limb, which block out some portions of the Sun's disk while revealing others just before or after totality. ABOVE: P. HORÁLEK/ESO. RIGHT: COURTESY OF M.E. BAKICH LIBRARY

not total from Jerusalem — in other words, not nearly dark enough to be described as “darkness.” Additionally, many Christian scholars suspect the crucifixion occurred later, likely in either the year 30 or 33, and that the reported darkness may have been caused by a massive dust storm, rather than a solar eclipse.

The eclipse on March 20, 71, stands out because in a book titled

De Facie in Orbe Lunae (*On the Face Which Appears in the Orb of the Moon*), the Greek philosopher Plutarch described the corona. This outer atmosphere of the Sun had doubtless been seen during hundreds of total solar eclipses prior, but Plutarch was the first to write of it, saying, “Even if the moon, however, does sometimes cover the sun entirely, the eclipse does not have duration or extension; but a kind of light is visible about the rim which keeps the shadow from being profound and absolute.”

After Plutarch's account, it would take another 266 years before someone described another solar feature seen during an eclipse. That happened when a member of the Roman Senate, Julius Firmicus Maternus, authored the earliest description of a prominence. His observation is even more remarkable because the July 17, 334, event was an annular eclipse — and he wasn't even on the path of annularity. He watched it from Sicily, where it was an 88-percent partial eclipse.



July 19, 418, marks the first total solar eclipse (of which we have a record) during which a comet was seen. Turkish-born Church historian Philostorgius wrote in Book XII of the *Epitome Historiae Ecclesiasticae*: “When Theodosius had reached adolescence, on the nineteenth of July at about the eighth hour, the sun was so completely eclipsed that stars appeared. There appeared in the sky with the sun while in eclipse a cone-shaped light, which some out of ignorance called a comet. But it showed none of the features of a comet. For the light did not form a tail, nor was it at all like a star; rather, it resembled a great lamp-flame appearing on its own,

The ancient Chinese text reads: “On the first day of the last month of autumn, the Sun and Moon did not meet harmoniously in Fang.” What an understated way to describe an eclipse!

with no star under it to form a wick for it. Its movement was also different. It began where the sun rises at the equinox, from there passed over the last star in the Bear's tail, and went on slowly westward."

Clearly, Philostorgius did not believe the object was a comet. Many reports from Europe and China, however, prove that it was, so the event goes down as the first reports of a comet seen during the total phase of a solar eclipse.

The second millennium

The first famous total solar eclipse after the year 1000 was on Aug. 2, 1133. Visible in Scotland, totality was

nearly 4½ minutes in length. And this eclipse provides just one of many historical examples of people wrongly associating a celestial spectacle with an earthly event.

In his *Historia Novella*, written between 1140 and 1143, English historian William of Malmesbury linked this eclipse with the death of King Henry I: "The elements manifested their sorrow at this great man's last departure from England. For the Sun on that day at the 6th hour shrouded his glorious face, as the poets say, in hideous darkness agitating the hearts of men by an eclipse; and on the 6th day of the week early in the morning there was so great an earthquake that the ground appeared absolutely to sink down; a horrid noise being first heard beneath the surface."

The problem is that the eclipse and

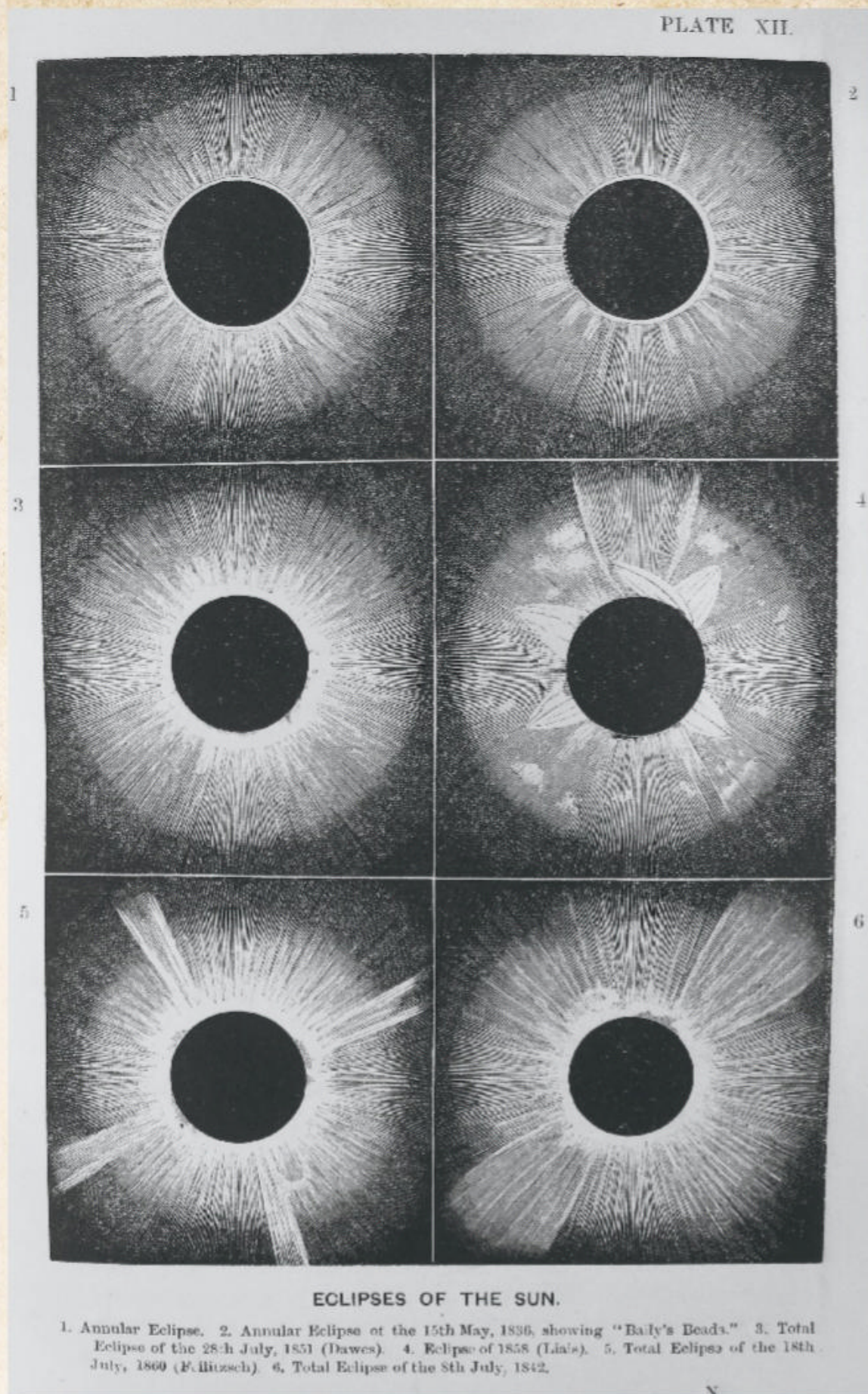
the death occurred in different years. The account implies, 19th-century author Mabel Loomis Todd wrote in her book *Total Eclipses of the Sun*, "that Henry must have died in 1133, which he *did* not, or else there must have been an eclipse in 1135, which there *was* not. But this is not the only labyrinth into which chronology and old eclipses, imagination and computation, lead the unwary searcher." Quite true.

For now, we'll stay in Scotland: The next three total solar eclipses are memorable because of the nicknames the Scottish people gave them. The June 17, 1433, eclipse's totality lasted up to 4 minutes 26 seconds. It is remembered as the "Black Hour." On March 7, 1598, a total eclipse known as "Black Saturday" had a duration of totality of 1 minute 29 seconds in the

Johann Christian Schoeller painted this scene depicting crowds of people viewing the July 8, 1842, total solar eclipse over Vienna, Austria.

JOHANN CHRISTIAN SCHOELLER (ARTIST), SONNENFINSTERNIS, 8. JULI 1842, 1842, WIEN MUSEUM INV.-NR. 65303, CC0 ([HTTPS://SAMMLUNG.WIENMUSEUM.AT/EN/OBJECT/418541/](https://sammlung.wienmuseum.at/en/object/418541/))





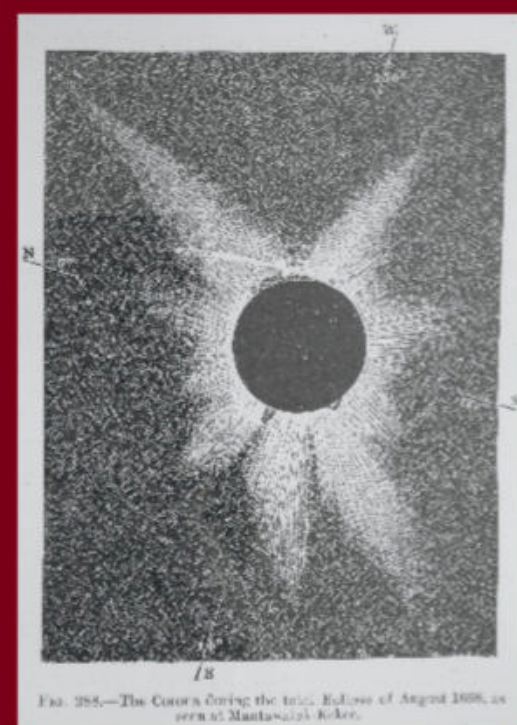
As the Moon blots out the Sun, the ethereal solar corona appears in the sky. It never looks the same twice, as evidenced by these sketches, each of a different annular or solar eclipse, which appeared in Mabel Loomis Todd's 1898 book *Corona and Coronet*. Other phenomena appear in the drawings as well, including Baily's beads and solar prominences. COURTESY OF M.E. BAKICH LIBRARY

southeastern part of the country. Finally, "Mirk Monday" refers to the eclipse that occurred April 8, 1652. In Edinburgh, residents experienced 2 minutes 47 seconds of totality.

More fleeting was the hybrid solar eclipse (one that is annular at one or both ends of the path and total in the middle) of Jan. 24, 1544: Totality lasted a mere 16.3 seconds. Dutch mathematician Gemma Frisius

observed this event as a 95-percent partial eclipse from Belgium. Later, he published what may be the first illustration of a camera obscura, a darkened room with a hole (later versions used a lens) at one end that projects an image from outside onto the wall. Frisius' illustration shows the eclipse projected into the room.

The next total solar eclipse worthy of our list was observed at sea by a



TOP: A series of sketches show red solar prominences visible during the Aug. 18, 1868, eclipse. It was during this eclipse that Pierre Janssen discovered a mysterious emission line in the solar spectrum — one due to then-unknown helium. COURTESY OF M.E. BAKICH LIBRARY

BOTTOM: This detailed sketch of the corona and other solar features during the Aug. 18, 1868, totality appeared in an 1872 book by Heinrich Schellen. COURTESY OF M.E. BAKICH LIBRARY

Spanish admiral, Don Antonio Ulloa. His ship wasn't on an eclipse expedition; its course simply intersected the path of totality. Talk about being in the right place at the right time! On June 24, 1778, he and his crew were heading to Cape St. Vincent from the Azores when they observed a totality lasting 4 minutes 50 seconds.

Of the sighting, Ulloa wrote, "The darkness was such that persons who

were asleep and happened to wake, thought that they had slept the whole evening and only waked when the night was pretty far advanced. The fowls, birds, and other animals on board took their usual positions for sleeping, as if it had been night.”

By the way, this was the first total solar eclipse observed in a brand-new country called the United States. The path made landfall in modern-day Louisiana (still then a French colony), where totality lasted 4 minutes 31 seconds. It crossed into the U.S., then exited at the Atlantic Coast of Virginia after totality had stretched to a whopping 5 minutes 22 seconds.

The 19th century

Before 1801, eclipse observations were largely descriptive in nature and primarily made to check the mathematical calculations of astronomers. It was during the 19th century, however, that science — mainly through the tools of spectroscopy and photography — entered the picture.

The century’s first notable total solar eclipse occurred June 16, 1806, and crossed the U.S. from Arizona to Massachusetts. The path of totality — whose length started at 3 minutes 13 seconds and stretched to 4 minutes 48 seconds — touched 21 states (or areas that eventually would become states). Observers on the center line from positions north of Wichita,

Kansas, through the state of Massachusetts experienced more than 4 minutes of totality.

As I’ve mentioned, Plutarch described the corona he saw in A.D. 71. But it was the Spanish astronomer José Joaquín de Ferrer who gave the Sun’s outer atmosphere that name after viewing the 1806 eclipse. He chose the word *corona* because it’s the Latin word for “crown.” He was also one of the first observers who gave a convincing argument that this extended feature was part of the Sun; prior astronomers had debated whether it belonged to the Sun or the Moon.

The annular eclipse of May 15, 1836, has an important place in history because an astronomer who observed it coined a term for a phenomenon millions of viewers had seen before and have seen since.

English astronomer Francis Baily experienced 4 minutes 22 seconds of totality from Jedburgh, England. Like others before him — including Edmond Halley, who wrote of “Points on the Moon’s Limb” during a 1715 eclipse — Baily described dots of sunlight often seen just before and just after totality as well as during some annular eclipses. He called these points of light “beads,” and explained that they appear because sunlight is passing through valleys located at the Moon’s irregular edge; these openings briefly let us see minuscule areas of

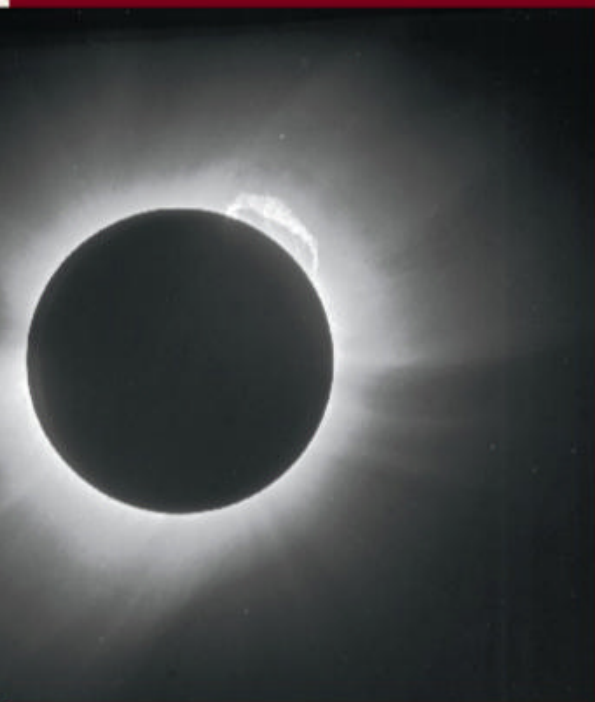
the Sun’s surface. As a result of Baily’s observations and work, we now call that phenomenon Baily’s beads.

The next total solar eclipse on our list — July 28, 1851 — is important for two reasons. First, English amateur astronomer and author George F. Chambers wrote that it

Like others before him, Baily described dots of sunlight often seen just before and just after totality, as well as during some annular eclipses. He called these points of light “beads.”

was the first that spawned dedicated eclipse expeditions. The path of totality stretched from what is today western Canada to Ukraine. European astronomers, however, targeted Norway and Sweden. Bergen, Norway, and Gothenburg, Sweden, both major cities, experienced 3 minutes 17 seconds of totality.

The second reason this event is



LEFT: The total solar eclipse of 1919 famously provided proof that general relativity is correct. In addition to the solar corona and a large prominence, also visible are background stars in Taurus the Bull, whose apparent positions were used to prove Einstein’s theory. F.W. DYSON, A.S. EDDINGTON, & C. DAVIDSON



RIGHT: The 2017 total solar eclipse made history as more than 10 million people viewed it. The next total solar eclipse over the U.S. is in 2024 — and now is the time to start planning how you will see it. NPS/JACOB W. FRANK

notable is because during the 2 minutes 56 seconds the Moon obscured the Sun at the Royal Observatory in Königsberg, Prussia, a photographer named Johann Julius Berkowski took the first successful image of totality. He connected a camera that held a daguerreotype plate to a 2.4-inch refractor and made an 84-second exposure.

During the total solar eclipse of Aug. 18, 1868, two astronomers, Pierre Jules César Janssen of France and J. Norman Lockyer of England, each independently discovered a new line in the Sun's spectrum. Lockyer thought it showed an undiscovered element, which he named *helium*. (In Greek mythology, Helios was the Sun god.) Although scientists would later show that helium is the second most abundant in the cosmos, it wasn't found on Earth for another 27 years.

Also notable was the total solar eclipse of July 29, 1878, during which two groups of astronomers, while observing, discovered that more data could be gathered from higher-altitude locations. An American group chose to watch the eclipse from the summit of Pike's Peak, which rises to 14,115 feet (4,302 meters). A British group set up some 6,000 feet (1,829 m) lower. Later, when their views of the corona were compared, those from the higher elevation were markedly better than the ones at the lower site because the air was much clearer at the former.

Providing proof

The final total solar eclipse I want to mention is probably history's most famous because of its ties to Albert Einstein's theory of general relativity, which he published in full in 1916. The eclipse occurred three years later, on May 29, 1919, and the duration of totality — 6 minutes

51 seconds — ranked it as one of the longest in the 20th century.

Relativity proposed that space is curved by the mass of objects. To prove it, English astrophysicist Arthur Eddington led an expedition to the island of Príncipe off the west coast of Africa to photograph the Sun during totality. If the theory were true, the Sun's gravitational influence should shift the apparent position of nearby stars.

Another scientific expedition with the same goal went to Sobral, Brazil. When both teams returned from their travels, three members — Eddington, Frank Watson Dyson, and Charles Davidson — authored the paper "A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919."

In their conclusion, they state, "Thus the results of the expeditions to Sobral and Príncipe can leave little doubt that a deflection of light takes place in the neighbourhood of the

sun and that it is of the amount demanded by Einstein's generalised theory of relativity, as attributable to the sun's gravitational field." It was an amazing confirmation of Einstein's theory.

Make your own history

On April 8, 2024, you'll have a chance to etch such an event into your own historical record as a total solar eclipse sweeps across the U.S.

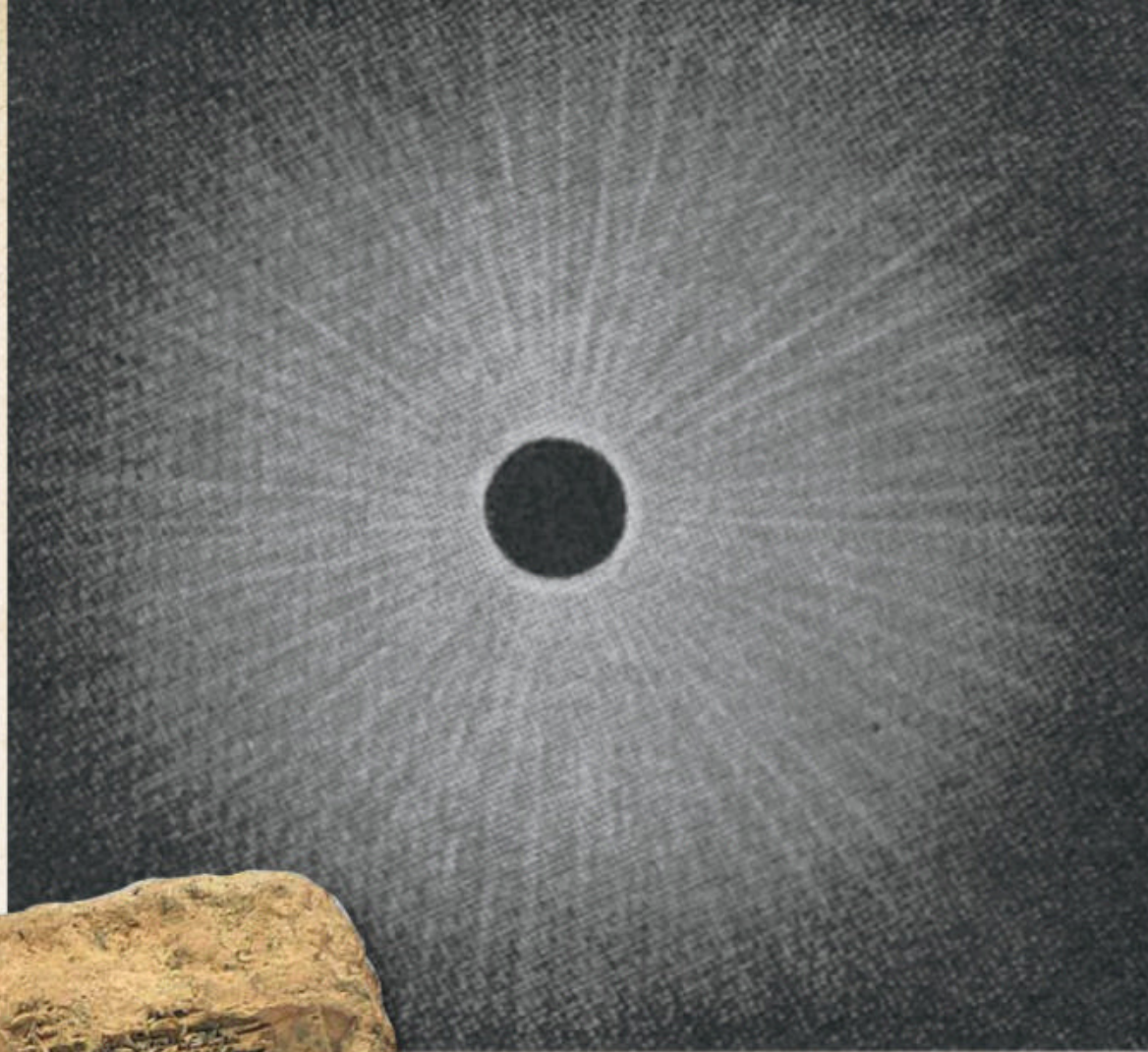
With durations of totality longer than 4 minutes from the Mexican border to Indianapolis, this will be as much a must-see event as the August 2017 total solar eclipse, whose path tracked from Oregon to South Carolina. More than 10 million people viewed that event. In 2024, some 31.6 million people will already live in the path, and millions more probably will travel to it. Make sure you're one of them. ☿

Michael E. Bakich is a contributing editor of *Astronomy* who will experience his 15th solar totality in 2024.



LEFT: Many cultures observed and recorded solar eclipses throughout antiquity. This Babylonian clay tablet is inscribed with a list of solar eclipses that occurred between 518 B.C. and 465 B.C.

NASA SUN EARTH DAY



ABOVE: In 1806, Spanish astronomer José Joaquín de Ferrer observed a stunning solar eclipse. Afterward, he gave the feature first described by Plutarch more than a millennium earlier a name: *corona*, Latin for "crown." JOSÉ JOAQUÍN DE FERRER

SIMULATE TOTALITY

Offering real-time rendering, this website is the perfect tool to preview the 2024 eclipse.

BY MICHAEL E. BAKICH

THE AUG. 21, 2017, total solar eclipse that swept across the U.S. revealed a need for a great deal of astronomy education for the general public. The lower 48 states had not seen solar totality since 1979, and people everywhere were clamoring for information on where they needed to be to see totality, what causes eclipses, and how to watch one safely. And, in retrospect, the astronomy community generally delivered fantastically well on all these accounts.

Dan McGlaun, a veteran of 14 total solar eclipses, participated in that effort by operating the now-defunct site www.eclipse2017.org, which (with over 200 million hits) successfully provided education and outreach for the 2017 total eclipse. For the 2023 and 2024 eclipses, he's created www.eclipse2024.org to host information on the events.

ABOVE: Explore the cities along the 2024 path of totality with the Eclipse Simulator map. For a complete set of instructions for the Map tool, select "View the Map Selection Tool Instructions" beneath the search bar.

LAPTOP: NATTSTUDIO/DREAMSTIME. ALL OTHER IMAGES IN STORY: WWW.ECLIPSE2024.ORG

RIGHT: This series of images shows the path of the Moon across the Sun from Radar Base, Texas, in 2024. A similar eclipse animation is available for each city page at www.eclipse2024.org.

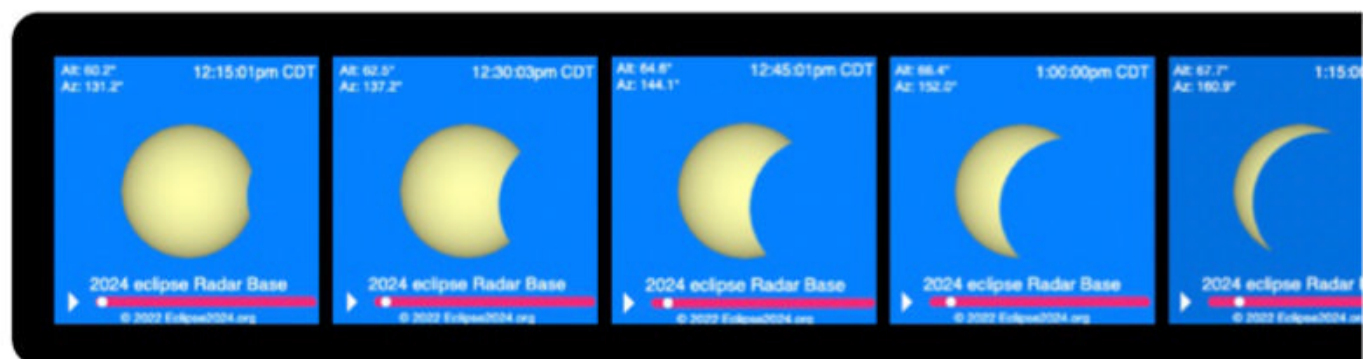


Meet the Simulator

A major part of McGlaun's effort is his Eclipse Simulator, online software that shows an accurate preview of the 2024 total solar eclipse from any location in North America. For those looking to pick the best location to view the event, the program simulates the eclipse and its duration. For educators, it helps teach about features seen during totality. And researchers might even want to use it to plot the Sun's position, edge effects along

the path of totality, and the movement of Bailey's beads.

Unlike other simulators, McGlaun's shows full-sky views, including foregrounds a user can customize, an overview shadow map, and accurate sky darkening. Users can also zoom in to see Bailey's beads (created with data from NASA's Lunar Reconnaissance Orbiter and custom calculations), examples of prominences, the chromosphere, the diamond ring, and several sample coronas.



Time sliders and a clock feature allow the user to run the eclipse in simulated real, compressed, or accelerated time.

McGlaun performed all eclipse calculations himself using elements calculated by American eclipse expert Fred Espenak and standard methods taught by Belgian astronomer Jean Meeus, among others. He devised his own methods for making line-of-sight calculations for the appearance of Baily's beads from any given location. One of the only things he didn't do was program the software — he works with developers to implement his calculations and techniques.

Following the 2017 eclipse, McGlaun created a database of 140,000 cities, offering general information for the 2023 and 2024 eclipses for all of them on a page rendered for each location. At first, he developed and placed small animations of the eclipse on each city page, then realized it also would be interesting to show the edge effects that eclipse chasers are so fond of. So, he developed the processes that enable the simulator to show the diamond rings, Baily's beads, the corona, and the chromosphere, making the closeup animations more complete.

More is better

Once the basic simulator was complete, McGlaun knew he had something that could be of real value for both first-time eclipse viewers and veteran chasers, either of which might want to know how the eclipse will look from a given location. So, he began a two-year effort to add even more features like umbral darkening, variable coronas, statistically placed prominences, planets and stars, sunrise and sunset effects, and the ability to zoom in and out. He also added the option to show the eclipse at any moment and to change the rate at which time elapses.



For details on how to use the simulator — shown here for Radar Base, Texas, the first place in the U.S. to see totality in 2024 — extend the collapsed menu in the upper right and select "Instructions."

By then, the simulator could show eclipses from over 140,000 cities. Additionally, it incorporated variable foregrounds, solar and lunar outlines, glare, a feature to allow closer study of Baily's beads, and an eye safety warning that disappears when totality begins and reappears when it ends. He also added a map that shows an overview of the Moon's shadow and pops up whenever the eclipse magnitude is greater than 98 percent.

With a full-fledged working simulator, McGlaun was determined to offer it as a "go-to" tool for anyone from casual observers to eclipse enthusiasts. He developed a complete set of instructions and worked with translators to translate the site into French, Spanish, and Portuguese. He also developed a process to add additional eclipses, to ensure the tool stays relevant into the future.

Currently, the Eclipse Simulator is a highlight of the www.eclipse2024.org site, but there's more. McGlaun has extracted videos from the simulator and, with the help of video editors, composers, artists, and his talented developers, created more than 10,000 YouTube videos (see the bottom QR code on this page) showing eclipses from various locations. You can watch the eclipse any time!

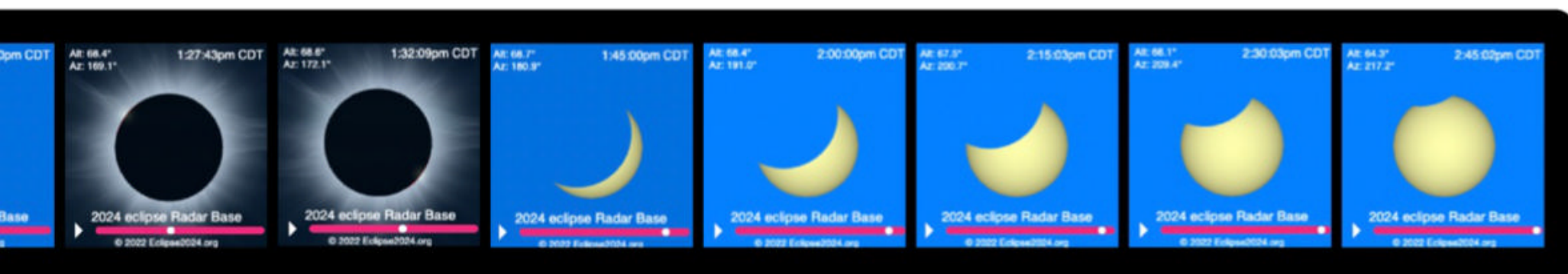
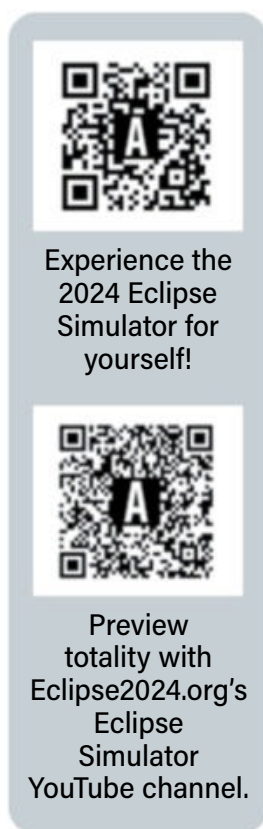
As of this writing, the simulator contains the April 20, 2023, hybrid solar eclipse that will pass over Western Australia and Indonesia, the Oct. 14, 2023, annular eclipse that will cross North and South America, and the April 8, 2024, U.S. total solar eclipse. And in the future, the simulated views might be even more intricate: McGlaun has been asked to add weather, crowd noise, the sounds of birds and insects, and even the possibility of controlling a user-connected USB fan to simulate the temperature drop that takes place during totality. Stay tuned!

Try it for yourself

"What we've achieved isn't perfect, but I believe it's the best simulator out there," McGlaun says. "It's fun to show people who've never seen an eclipse the difference between a 98-percent-partial and a total eclipse — and then tell them they'll have to see the real thing to get the full effect."

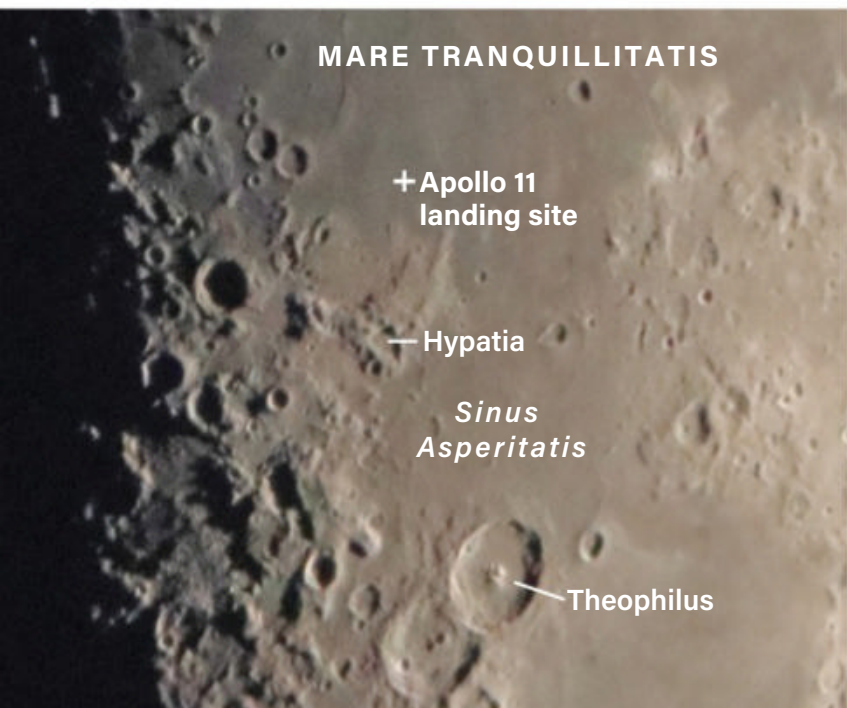
Developing the Eclipse Simulator has been a long and difficult effort, but those who have seen it agree that it's been worth it. Perhaps the coolest feature is that McGlaun is able to offer it to everyone free of charge. Be sure to check it out at www.eclipse2024.org.

Michael E. Bakich is a contributing editor of *Astronomy* and co-author of *Field Guide* to the 2023 and 2024 Solar Eclipses.



Atwood's flash

The Moon may be dead geologically speaking, but not through a telescope.



The crater Hypatia is located on the southwest edge of Mare Tranquillitatis (Sea of Tranquillity), with its southern lip jutting into the northwest shore of Sinus Asperitatis (Bay of Roughness). North is up, east is right. STEPHEN JAMES O'MEARA



BY STEPHEN JAMES O'MEARA
Stephen is a globe-trotting observer who is always looking for the next great celestial event.



The dynamic interplay of light and shadow across the lunar face is a perpetual source of visual wonder — and, sometimes, puzzlement.

Nearly 40 years ago, Terry Atwood of Shreveport, Louisiana, saw one such display in the crater Hypatia. The feature lies in a tiny promontory of equatorial lunar highland, just south of the Apollo 11 landing site

in Mare Tranquillitatis (Sea of Tranquillity). The crater's name honors Hypatia of Egypt (circa A.D. 370–415), the first woman known to have made a substantial contribution to the development of mathematics.

Under the right geometry, a ray of sunlight can slice across Hypatia's otherwise shadowed crater floor. Such an event is likely best seen around a solar colongitude of 350° (or about 10° shy of First Quarter) — with the Sun about 13° high in the lunar sky as seen from Hypatia. In that case, the events are likely to next occur Feb. 27 at 1h26m UT and April 27 at 3h30m UT.

But on Jan. 16, 1986, Atwood saw a phenomenon which may be a visual prelude to the well-known ray. He was using his 8-inch Cave Astrola reflector to search for the tiny craters named after the Apollo 11 astronauts when, at 1h13m UT, he saw two rays of light suddenly “flash” into view in Hypatia. The view was akin to being in a dark room when a door suddenly opens a crack, allowing light to stream in. “The light flashed on,” Atwood says, “and stayed on.”

At the time of Atwood's sighting, the Moon was five and a half days after New, at colongitude 333° — well before the expected ray should appear on the crater's irregular floor. Indeed, Atwood's friend, Roy Parish (former coordinator of the Lunar Section of the Association of Lunar and Planetary Observers), determined that Atwood's flash took place when the Sun was about 3.5° below the lunar horizon, as seen from the

Hypatia's life and murder has been the subject of many works of literature, theatre, and film. This 1890s woodcut portrait shows British actress Julia Neilson in character as Hypatia. ©THE TRUSTEES OF THE BRITISH MUSEUM



center of the Hypatia's floor. However, Parish notes that the Sun's altitude would only have to be about 1° high to illuminate the hilltops north of the crater's floor. (The crater has no central peak.)

Atwood's sighting, then, just may be the earliest known record of the first glints of sunlight slipping through the gap in Hypatia's eastern wall on its way to start the ray. It's possible that atmospheric seeing may have produced distortions that magnified the apparent flash.

But why then did Atwood see *two* rays? Here is a hypothesis. The United States Geological Survey's *Geologic Atlas of the Moon* shows that Hypatia's walls have a high albedo (meaning they are highly reflective), suggesting the presence of freshly exposed volcanic material. Furthermore, an image of the crater taken by Apollo 16's mapping camera shows several upright bright streaks on the crater's western wall just opposite the breach. The higher elevation of these bright streaks might explain Atwood's dual-ray phenomenon and why

it appeared at such a low Sun angle.

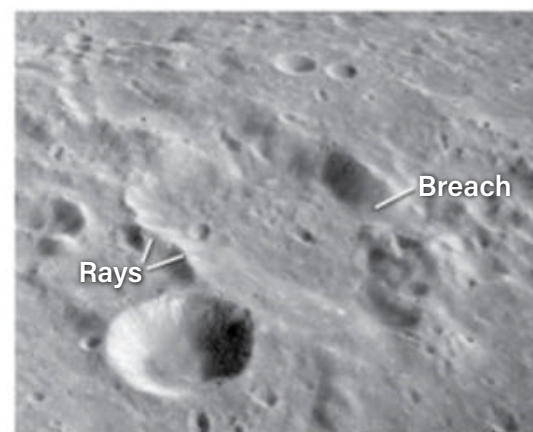
Is it possible, under the right viewing geometry, for sunlight to glint off structures of volcanic glass within the streaks as the Sun nears rising, creating a striking prelude to the Hypatia ray? More observations are needed to solve this mystery.

As Atwood says, “I remember a professor saying that the faintest note is worth the fondest memory.” Atwood's words recall those of Hypatia's father, also a renowned

mathematician, who is said to have told her, “Reserve your right to think, for even to think wrongly is better than not to think at all.”

As always, send your thoughts and observations to sjomeara31@gmail.com.

Atwood saw two rays of light suddenly “flash” into view in Hypatia.

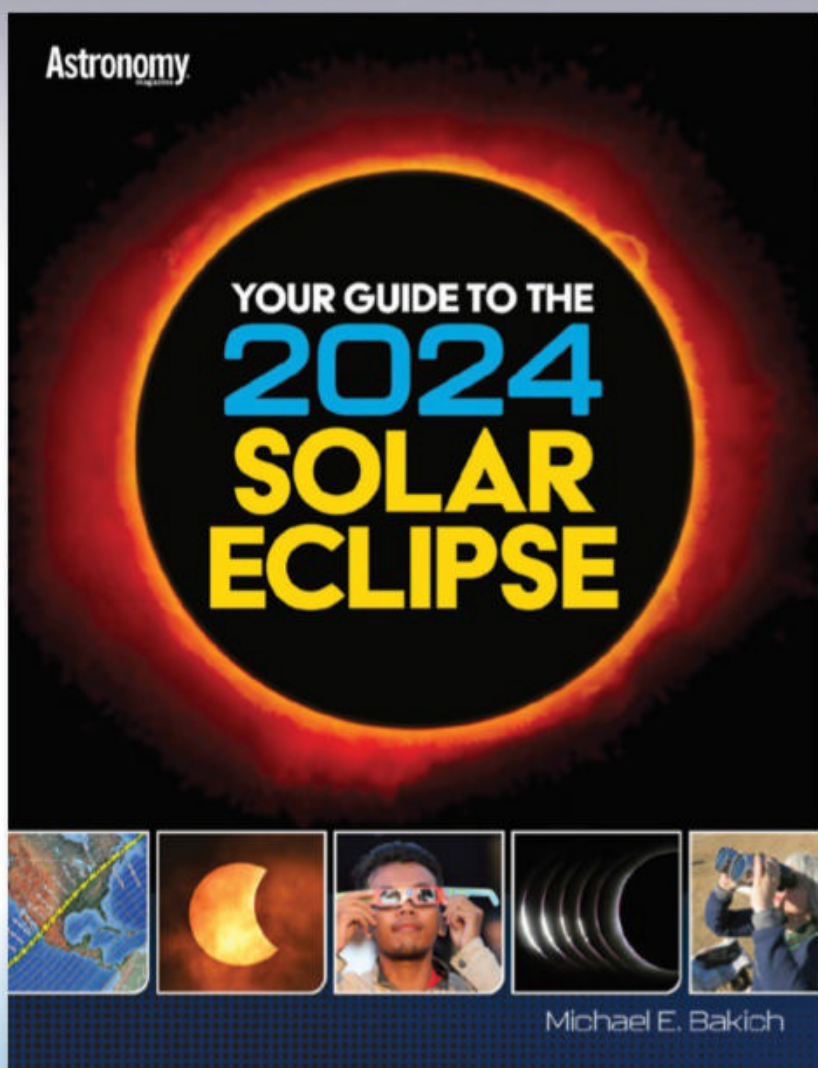


The breach in Hypatia's eastern wall and raylike streaks in the crater's western wall are visible in this Apollo 16 image. The fresh circular crater at lower left is Hypatia A. North is up and east to the right. NASA/WIKIMEDIA COMMONS



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Machholz's marathon

Honor the comet hunter's legacy with a Messier run.



Don Machholz was one of the great comet hunters. But perhaps his greatest contribution to observers is the Messier marathon.

MICHELE MACHHOLZ/
WIKIMEDIA COMMONS



Last summer, the global amateur astronomer community was rocked when it lost one of its giants. Don Machholz from Arizona passed away suddenly on Aug. 9, 2022, at the age of 69. Don was a preeminent visual comet hunter with 12 discoveries to his credit. His most recent was Comet C/2018 V1 (Machholz–Fujikawa–Iwamoto), discovered Nov. 7, 2018.

Don was also one of the originators in the 1970s of the much-beloved Messier marathon. He realized that around the time of the vernal equinox, the Sun is positioned such that all the Messier objects — save for M30 in Capricornus — are visible sometime between sunset and sunrise. (And if you want to get technical, even M30 is possible just before dawn, provided you live south of latitude 30° north.)

Observers can take on any version of the marathon they want. If you're just beginning, you might try out a seasonal mini-marathon. Or, if you're up to the challenge, try to spot as many of the 109 objects through binoculars and telescopes as you can in a single sunset-to-sunrise marathon observing session. For added difficulty, traditionalists run the marathon without using go-to controls, setting circles, or similar aids.

Often, attempts are confounded by moonlight around the vernal equinox. But not this year: New Moon is on Tuesday, March 21, making 2023 perfect for running the marathon in honor of Don's memory. Here are some quick tips if you are a marathon newbie.

You may be thinking, "How can I see all the Messier objects through binoculars?" True, some may elude you. It's not so much a matter of can you see them all, but rather how many can you see? Back in high school, I found 85 objects through 7x35 binoculars. About 20 years later, I saw 101 in a single night through 11x80s.

You'll need a clear, dark sky with good views to the west and east. Those are critical directions for the evening and morning "rush-hour" objects, respectively. Rush-hour objects either set or rise in twilight's glow.

You will also want a good star atlas, like *Astronomy's The Complete Star Atlas*, to guide you along your journey. Alternatively, an online printable atlas, like www.freestarcharts.com/messier, is a good choice.

Your binoculars should be mounted on a tripod or other support, since you will be going between charts and binoculars all night long.

Like running a road marathon, you need a strategy for this celestial race, especially for the early evening and early morning. I always try to nab the brighter evening objects — such as the Orion Nebula (M42) and Pleiades (M45) — before the sky fully darkens.

Then, as the sky becomes dark enough, the race against time begins.

Those rush-hour objects (see table at right) are easily lost in twilight if not glimpsed quickly enough.

Realistically, some targets that are marginally visible even when high in the sky may elude you due to their low altitude at this time of year.

As you make your way through the rest of winter's clusters, nebulae, and early spring's challenging galaxies, the next hurdle becomes visible around midnight: the Coma-Virgo realm of galaxies. Fourteen Messier objects lie within a 10° by 10° area between Denebola

(Beta [β] Leonis) in Leo and Vindemiatrix (Epsilon [ε] Virginis) in Virgo. Here, patience is a virtue, since none of the galaxies shine brighter than magnitude 8.4. Most are between magnitude 9 and 10. A detailed chart is a must. Contact me through my website (below) and I'll be happy to send you a copy of the one I use.

By the time you're out of this galactic realm, the summer stars are rising. The air may be cold, but those superb summer treasures are bound to warm you. Visit each only briefly because before you know it, it's morning and the race is coming to an end.

Good luck if you decide to give the marathon a run. I would enjoy hearing your results; contact me through my website, philharrington.net. And until next month, remember that two eyes are better than one. ☾

Rush-hour objects

Evening rush hour	Morning rush hour
M31	M55
M32	M75*
M110*	M15
M77*	M2
M33	M72*
M79*	M73*
M74*	M30#
* - may not be visible through binoculars during the marathon # - only possible south of about latitude 30° N	

Don was also one of the originators of the much-beloved Messier marathon.



BY PHIL HARRINGTON
Phil received the Walter Scott Houston Award at Stellafane 2018 for his lifelong work promoting and teaching astronomy.



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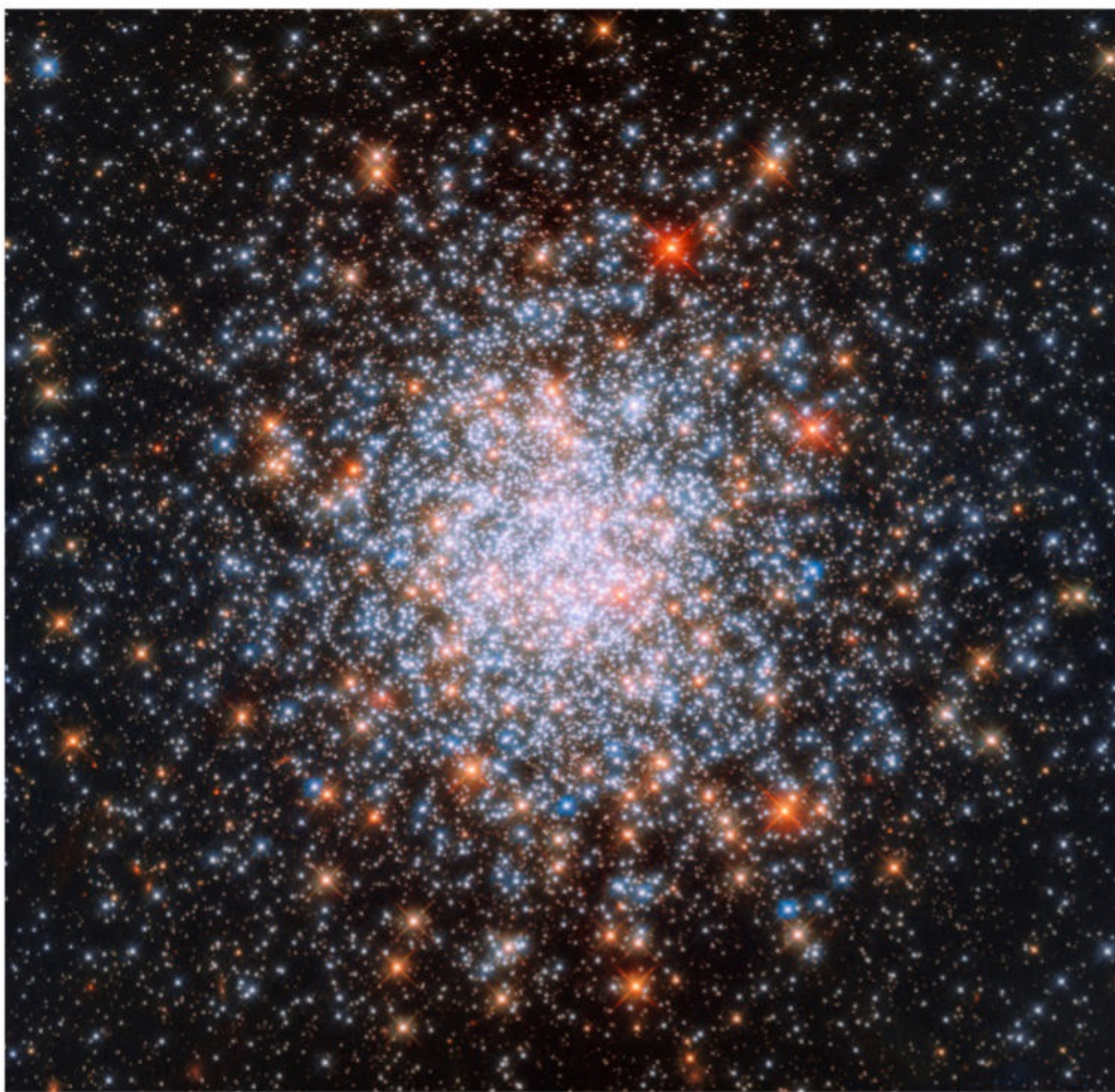
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Located at the edge of the Large Magellanic Cloud, NGC 1866 is close enough for individual stars to be studied. This globular cluster is also unique because it is surprisingly young and filled with different generations of stars. ESA/HUBBLE & NASA

Astronomical fossils

Q | SINCE THEY LACK DARK MATTER AND CENTRAL BLACK HOLES, HOW DID GLOBULAR CLUSTERS FORM?

Sasi K. Chandran
Wake Forest, North Carolina

A | Globular clusters are the fossils of the astronomical world. We know they are very old, having formed shortly after the Big Bang. Furthermore, they must be pretty robust, since many have survived until the present day. But the exact details of how these clusters formed is still the subject of much research.

Observations of nearby globulars indicate that they do not contain dark matter, but that does not preclude them having formed originally within mini dark-matter halos.

However, we see young (i.e., a few billion years old) star clusters within the Magellanic Clouds with many of the characteristics of globular clusters. In other words, if we could observe those star clusters approximately 10 billion years from now, we would probably call them globular clusters. These proto-globulars in the Magellanic Clouds are not surrounded by mini dark-matter halos, so it's likely that the old globular clusters we see now were also free of dark matter earlier in their lifetime.

The subject of whether globulars contain a central massive black hole is controversial. For every claim, there seems to be a counterclaim. Certainly, globulars contain stellar-mass black holes (left over from the deaths of massive stars or mergers of stellar remnants), but whether these can accumulate at the center of such a cluster to form a massive black hole thousands of times the mass of our Sun remains unclear.

All large galaxies host a system of globulars. Our Milky Way contains around 200 such clusters; some are found in the bulge and disk, but most are in our galaxy's halo. Interestingly, only a fraction of the Milky Way's globular

clusters formed originally in our galaxy — most have been added over time as the Milky Way swallowed the dwarf galaxies in which they originally formed. (It's estimated that around half a dozen dwarf galaxies have merged with and been disrupted by the Milky Way as it grew.)

While you might expect that globular clusters would be scattered by these mergers, their robustness means that they are still with us today, while the original host galaxy's stars are dispersed. So, next time you look at a globular cluster with a telescope, consider that it might be an alien object formed outside the Milky Way. It may even have been the former nucleus of a dwarf galaxy!

Duncan Forbes

*Professor, Centre for Astrophysics & Supercomputing,
Swinburne University, Melbourne, Australia*

Q | HOW FAR BACK IN TIME WILL JWST BE ABLE TO CAPTURE LIGHT? HOW DOES THAT COMPARE TO THE FIRST LIGHT GENERATED AFTER THE BIG BANG?

Jim Doty
Perry Hall, Maryland

A | The universe is 13.8 billion years old. The oldest light ever observed was seen by NASA's Cosmic Background Explorer (COBE) mission. Launched in 1989, COBE measured the cosmic microwave background — the faint relic radiation filling all of space — created just a few thousand years after the Big Bang.

The James Webb Space Telescope (JWST) is designed to explore a subsequent epoch in which the universe was roughly 100 million years old. During this time, the first stars and galaxies formed. Thus, researchers expect that JWST will be able to study the earliest galaxies and supernovae produced by the universe's first stars.

JWST's large aperture and infrared capability enable astronomers to explore, for the first time, this period of galaxy formation. These data will help astronomers determine which of their theoretical models of how the universe evolved is correct.

Matt Greenhouse

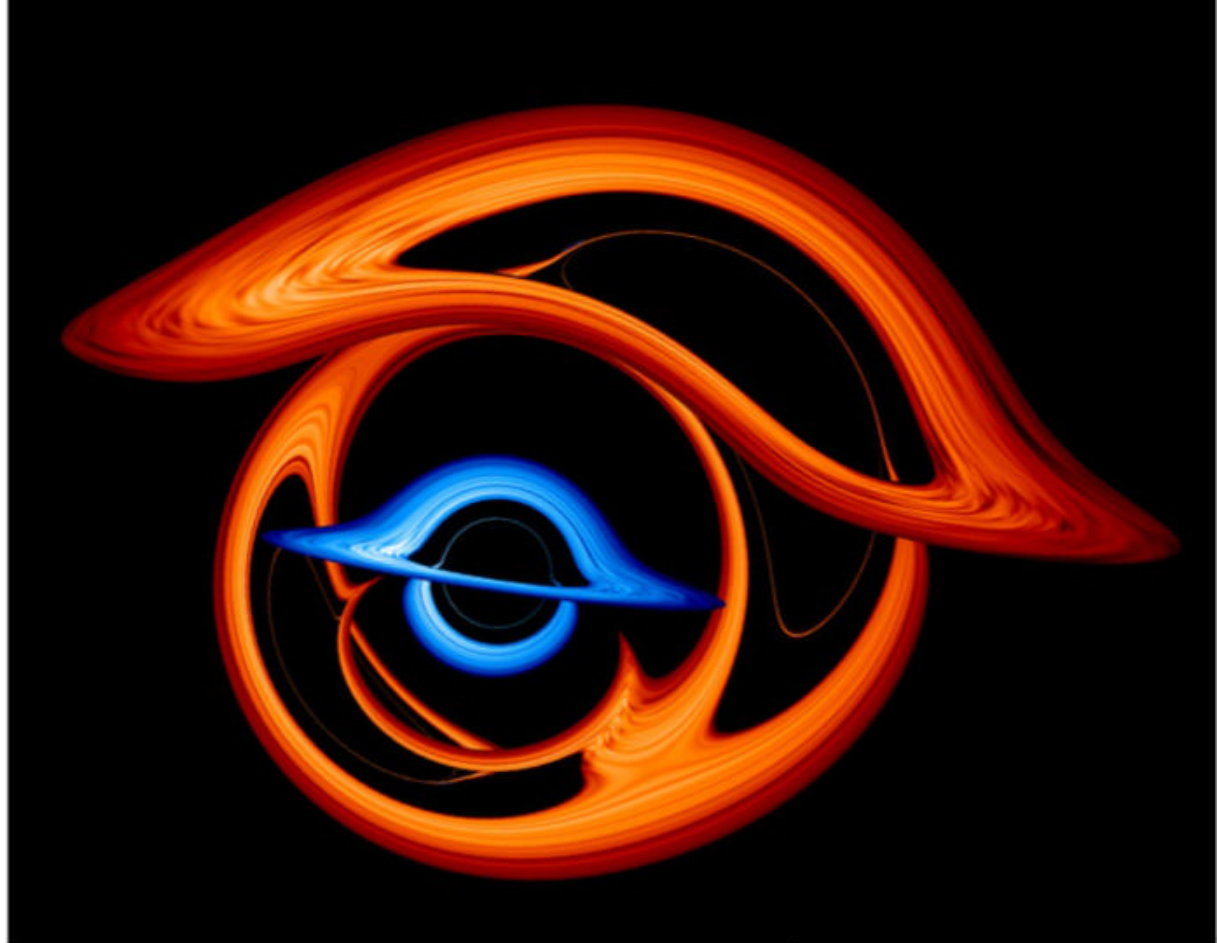
*Science Instrument Payload Project Scientist,
James Webb Space Telescope Program, NASA, Washington, D.C.*



JWST's first deep field revealed distant galaxies (and the earliest known globular clusters) after a mere 12.5-hour observation of the region centered on SMACS 0723. NASA, ESA, CSA, STSCI

Q | WHY DOES THE COLLISION OF SUPERMASSIVE BLACK HOLES GIVE OFF LOW-FREQUENCY GRAVITATIONAL WAVES COMPARED TO STELLAR-SIZED BLACK HOLE COLLISIONS?

Tyler Belnap
Chicago, Illinois



A | Einstein's theory of general relativity states that space and time are interwoven into a single continuum. The gravitational pull of massive celestial bodies like stars or black holes corresponds to distortions in this space-time fabric. Black holes cause extreme warping of space-time — they are objects that have so much gravitational pull, not even light can escape. The point of no return is called the event horizon.

There are two main classes of black holes (though astronomers suspect there are a few more categories). Smaller black holes that form from the deaths of massive stars or the mergers of stellar remnants are called stellar-mass black holes. This type weighs tens of solar masses to 100 solar masses. Supermassive black holes, on the other hand, live in the centers of galaxies and are millions to billions of times heavier than the Sun.

As pairs of black holes orbit one another, they produce ripples that propagate through the space-time fabric at the speed of light. These ripples are called gravitational waves. These waves carry away the system's energy, causing the orbit to shrink. As a result, the black holes orbit faster and faster, increasing the frequency of the gravitational-wave signal.

Right before two black holes finally merge, their event horizons are touching. This is when the black holes are closest to each other and their orbit is fastest. Hence, this is when the maximum frequency of the waves will occur. The size of a black hole's event horizon increases with its mass, so supermassive black holes have much larger event horizons than stellar-mass black holes. Therefore, supermassive black holes will be much farther apart than their stellar counterparts when their event horizons are touching. And, since the distance between two supermassive black holes is larger, the frequency of gravitational waves produced will be lower than in the case of two stellar-mass black holes.

Lisa Drummond

Graduate Student, MIT Kavli Institute for Astrophysics and Space Research, MIT, Cambridge, Massachusetts

This artist's concept shows how, in addition to warping space-time itself, a black hole's extreme gravity distorts our view of its partner as the two eclipse one another during their death spiral. NASA'S
GODDARD SPACE FLIGHT CENTER

SEND US YOUR QUESTIONS

Send your astronomy questions via email to askastro@astronomy.com, or write to Ask Astro, P.O. Box 1612, Waukesha, WI 53187. Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.

Cosmic portraits

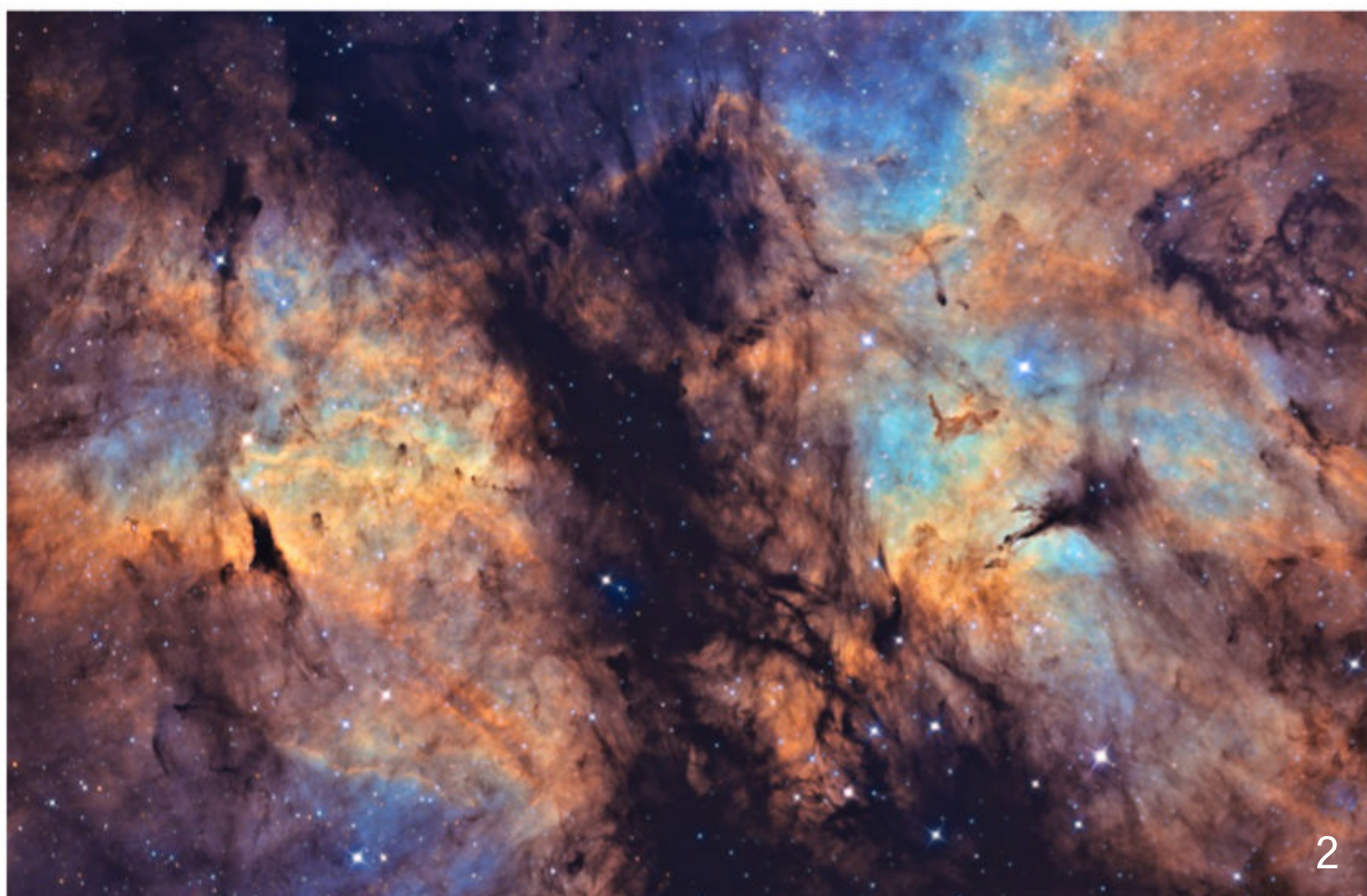


1. RED ALL AROUND

Mount Etna erupted in late 2022, lighting up the winter sky with fiery hues matching those of bloodshot Betelgeuse in Orion, Aldebaran (just to the right of Etna's plume), and Mars (brighter, above Aldebaran). The image was a 10-second exposure at ISO 6400 and a 15–35mm lens at f/4. • **Gianni Tumino**

2. BUTTERFLY IN THE SKY

The emission nebula Sharpless 2-108 in Cygnus also forms the Butterfly Nebula, with a dark dust lane (LDN 889) splitting its wings. This image represents 19 hours of exposure with a 14-inch scope in Hubble palette filters. • **Rouz Bidshahri**





3. BUBBLY ROSE

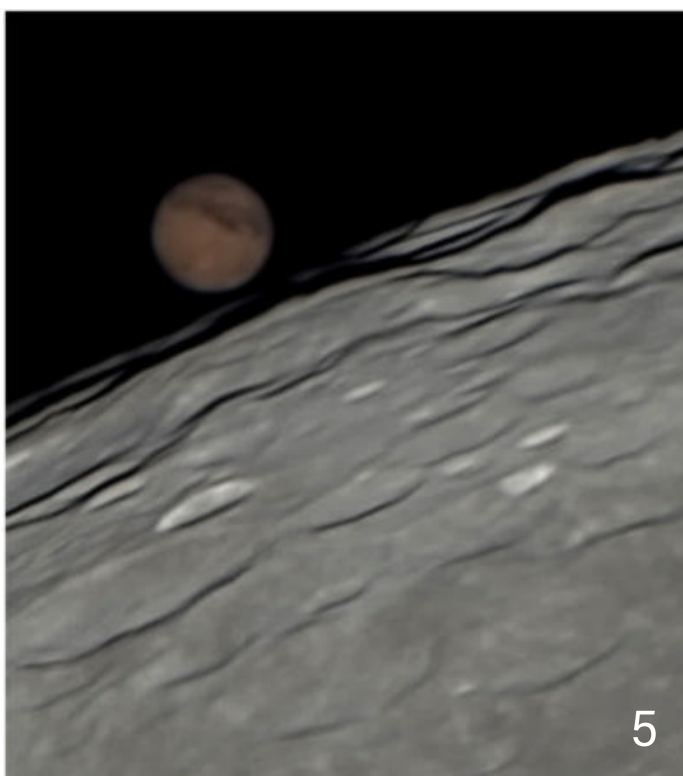
The Bubble Nebula (NGC 7635) is formed by the hot wind of a massive star 11,000 light-years away in Cassiopeia. It is expanding into a giant molecular cloud, which takes on a flowery appearance in this narrowband image. The photographer used an 8-inch scope to take nearly 40 hours of data.

• **Carl Gough**

4. FRIENDLY NEIGHBOR

The irregular dwarf galaxy IC 1613 in Cetus is a member of our Local Group, lying just 2.3 million light-years away.

Observations show it has a surprisingly low amount of dust, making its stars easier for astronomers to study. • **Fernando Oliveira de Menezes**



5. MARSRISE

Mars peers out from behind the limb of the Moon during the Dec. 7/8 lunar occultation of the Red Planet. This image is made of 500 stacked frames. • **Jon Bosley**

6. GOING IN CIRCLES

The stars take their nightly stroll around Polaris above a meditation labyrinth outside Tucson, Arizona. This photograph is a composite of 504 exposures, each 20 seconds long.

• **Charles Pevsner**



SEND YOUR IMAGES TO:

Astronomy Reader Gallery, P.O. Box 1612, Waukesha, WI 53187. Please include the date and location of the image and complete photo data: telescope, camera, filters, and exposures. Submit images by email to **readergallery@astronomy.com**.



BABY STARS EMERGE FROM FRIGID DEPTHS

Not all star-forming regions look as flashy as winter's glorious Orion Nebula (M42). The Taurus Molecular Cloud, for example, consists mostly of cold gas and radiates little light. But this stellar nursery does feature a few flickers of color. Sharpless 2-239, seen here, lies near the cloud's southern end just 2° northwest of Taurus' brightest star, 1st-magnitude Aldebaran. It contains two small clusters of modest stars — each likely less than 1 million years old — embedded within the glowing gas clouds. At a distance of about 450 light-years, the Taurus Molecular Cloud is likely the nearest large star-forming region. Astronomers captured this image with the 4-meter Mayall Telescope at Arizona's Kitt Peak National Observatory.

T.A. RECTOR (UNIVERSITY OF ALASKA ANCHORAGE) AND H. SCHWEIKER (WIYN AND NOIRLAB/NSF/AURA)

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